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NEW WORLD VISTAS

AIR AND SPACE POWER FOR THE 21ST CENTURY

HUMAN SYSTEMS AND BIOTECHNOLOGY VOLUME

NEW WORLD VISTAS
AIR AND SPACE POWER FOR THE 21ST CENTURY

HUMAN SYSTEMS/BIOTECHNOLOGY VOLUME

Executive Summary

This volume argues that the human is essential in every Air Force system at some level for exercise of command and control, and therefore all Air Force systems from design phase to final operating form must be "human-centered" to maximize system performance. It concludes that only human-centered systems can with certainty win the intense, complex, continuous conflicts of the future.

The case for human-centered systems is structured around eight topics, first presented as concise assertions for the future and then presented as fuller discussion papers in appendices to the volume. The topics are Human Information Processing/Decision Making, Cognitive Engineering, Personnel Selection and Classification, Precision Guided Training, Modeling and Simulation, Unmanned Air Vehicles, Global Presence (including Sustained Operations, and Logistics) and Biotechnology. Chemical/Biological Warfare is considered under Global Presence.

Human information processing/decision making is the most important topic in this volume. It is a principal component of every topic in this volume. The human is the most masterful information processor there is, but as the volume of information increases and time available for processing shrinks, human processing overload ensues and decision making suffers. Computers, artificial intelligence, decision aids, variable displays attuned to workload state, can take over much of this processing overload. Always the human operator must be cognizant of what the computer is doing and therefore capable of taking control when the need arises. The technologies to accomplish great advances in information processing by 2020 are ready for exploitation now, except in two critical areas: cognitive science and neurobiology of brain circuitry. A consistent level of support for these technology areas must be provided to achieve eventual interactive fusion of the brain with computer/machine for optimized decision-making.

Cognitive engineering must be included as an essential part of the design of the information displays and controls of future systems. As the Air Force moves into the "Information Age," either willingly or reluctantly, it is vital that the human-machine interface be understood, including a basic understanding of how humans process information and make decisions. Without this understanding, the Air Force will not only fail to take advantage of possible gains, but also may find that "improvements" can actually lead to deterioration of performance. It is essential that the Air Force undertake a long term research program to define the activities that people do best, what and how much information is needed for these activities, how to present this information to people so they make the best use of it, and then describe the automation required to support people's needs.

Personnel selection and classification technology will be much more precise in finding the best recruits and in matching these recruits to Air Force skill requirements. Advances in cognitive and especially non-cognitive screening instruments will make this possible. Whether the Air Force takes advantage of these advances depends on personnel policy decisions of the Department of Defense and the Air Force.

Precision Guided Training will eliminate today's "one size fits all" in training design whether for the individual or the unit. This means individualized training adapted by the individual to the individual's needs, capabilities, and desired outcomes. This vision is definitely achievable through more cost effective instructional devices. The benefits will be enormous and

can be forecast as training cost reductions of 50%, training time reductions of 30%, and increased proficiency in mission performance of 30%.

Modeling and simulation will be transformed by 2020 to include what is missing now, the characteristics of human behavior and performance. Progress in human body modeling, in human cognitive and non-cognitive behavioral modeling, and in human military task performance modeling will all make this transformation possible. While these modeling efforts are difficult to do, their very difficulty must not be allowed to impede progress and impede the recognition of the extraordinary value of incorporating human behavior and performance characteristics into the library of Air Force modeling and simulation systems.

Unmanned Air Vehicles (UAV) will be able by 2020 to perform virtually all the air combat tasks of piloted aircraft today. An effective user interface for these unmanned systems will allow the user to seamlessly move back and forth along a continuum from remote manual control to fully automated systems. Optimization of this interface may not involve transposition of information display systems and concepts designed for piloted aircraft to UAV remote control. Rather, optimization of this interface may require a very different set of psychomotor and perceptual relationships. While many UAV functions may be automated, this automation will bring new human tasks to monitor the automation and to maintain at all times a new kind of situation awareness.

Global Presence is a central characteristic of modern warfare. Warfare is continuous, with no pauses to allow an enemy to recoup. By 2020, fatigue management to allow sustained operations will have progressed such that the duty day could be extended with alertness drugs for three days continuously without a decrement in performance. The biological clock will be controllable and shiftable in order to accommodate the light/dark cycle of the body to operational needs anywhere on earth or in space. Recovery from sustained operations will also be controllable through sleep-inducing drugs. Delivery of these pharmacological controls will be titrated exactly to the needs of individual personnel through already emerging next-generation drug delivery systems. Logistics information, in digital format, will encompass all Air Force activities in a single seamless system operating globally, fused with the national support base located in US industry. The pacing technology in this transformation is information visualization technology. Electronic mock-ups, using animated 3-D graphics and virtual reality interfaces, will make it possible to visually review critical maintenance and repair tasks, to visualize the processes by which these functions are accomplished, to detect and correct sources of human error, and to generate maintenance instructions. Digital design archives will allow continuous upgrading of the logistical support system as Air Force weapons systems are introduced or modified.

Biotechnology and supporting fundamental sciences, especially neuroscience, are perhaps the most fertile fields in science today for generating revolutionary advances for future systems and operations. Potential applications of current research to Air Force needs fall into two categories: those directly related to human performance (e.g., drug enhancement of memory, enhanced electroencephalograph (EEG) workload monitors, and brain activated control of machines); and those involving improvements to Air Force weapon systems themselves (e.g., molecular optical information storage as in DNA coding, molecular optical computers, and new organic materials for ultralight/high strength structures).

It can be expected that the human/machine interface will be transformed by 2020 into a state that can fairly be called interactive fusion. The pacing science is brain mapping, and interpretation of brain circuitry electrical signals. The pacing technology is the EEG. The EEG, enhanced with an array of several hundred sensors instead of the usual clinical 19-20, embedded in a head mask worn tight to the scalp, shielded from exogenous radiation, will monitor various brain functions (e.g., visual, auditory, motor, attention, memory) and their level of effort and fatigue. The feasibility of this approach has recently been demonstrated, based on 20 years of research. Through advanced signal processing, one can forecast that the changing patterns of EEG signals, tied to computers, displays, and other machines, will become controllers of information presentation and content, and also on/off switches for automated information processing. Human information processing/decision making at the human/machine interface will be continuously optimized. This system will be transparent to the human user, so it will be employable in every Air Force mission circumstance. It will even be possible to drive the pharmacological management of fatigue during sustained operations by coupling brain state to sophisticated new drug delivery systems being devised in the private sector now.

Action. To achieve the overall vision presented in this volume, Air Force leadership must invest in the psychological, biological and computer sciences sufficient to force the frontiers of these sciences forward in areas where the Air Force benefits. Diverse as these sciences are, they fuse in support of the vision presented here. To convert advances in these sciences to practical Air Force applications, Air Force leadership must also invest systematically and long term in the development of enabling technologies based on these sciences, technologies repeatedly identified in this volume. These technologies include but are not limited to human modeling, both cognitive and physiological, workload and fatigue management systems, personnel assessment instruments, precision guided training, distributed interactive simulation for training, and information management responsive to human cognitive processes.

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1.0 Introduction

Sudden revolutionary progress comes rarely in science. Most advances come through small incremental steps, and the revolution evolves. Sudden revolutionary ideas in technology are more common; getting those ideas to a user product which is accepted, or which really does things better, is the rare event. This is true in the civilian world and in the Air Force alike.

This volume is mainly about revolutionary ideas for progress in science and technology, with a focus on the people of the Air Force. People are the most important resource of the Air Force. It follows that human-centered science and technology should be a central component of overall Air Force investment strategy for the future. This volume, while focusing mainly on revolutionary ideas, is in effect advocating a human-centered bias toward all Air Force science and technology investment now and into the future.

Far-out human-centered revolutionary ideas related to Air Force missions are not hard to find. Consider this partial list:

- Human control of machines by thought, no hands
- Human brain monitors of workload/fatigue
- Human body motion largely understood, modeled, and transferred through computer science/artificial intelligence into computer aided design programs
- Human body structure/performance largely understood, modeled, transferred to teleoperator design
- A human vaccine for chemical agents/toxins
- A human vaccine for biological warfare agents
- A pill to turn sleep on/off
- A pill to shift biological clock, offset jet lag
- A pill to improve learning and memory, enhancement of situation awareness
- A pill to protect against directed energy

Progress toward accomplishment of these revolutionary ideas will occur but assuredly will require a long time, for some beyond the time frame of New World Vistas. Single solutions to some of the complex problems represented on this list may never be achieved. If partial solutions are unsatisfactory, then the solution may be to eliminate the human altogether. This is an option, but not always.

There are also a number of less far-out evolutionary ideas with the potential to impact Air Force operations and mission capabilities in major ways. These include:

- Precision guided training that reduces training time by 30% and cost by 50%
- Training systems that increase mission effectiveness by 30%
- Instantaneous situation awareness tailored to task requirements

- Information displays and controls that reduce acquisition/interpretation errors by 20%
- Displays and controls that reduce operator workload by 20%
- A paperless maintenance system
- Cognitive engineering of jobs and provision of job-aids with artificial intelligence

Progress toward solutions to science and technology problems associated with these ideas is well underway. Continuing such progress and support of implementation forts will yield major significant benefits to the Air Force in terms of decreased cost, increased personnel performance, and increased mission capability. Such benefits can be achieved by 2020 and will continue in the future.

Structure of This Volume

The over-arching goal of this volume is the enhancement of Air Force system design and operations through appropriate consideration of the human sciences and technology. It is organized around several topics. Each topic is central to the success of Air Force missions now and into the far future. These topics are:

- Human Information Processing/Decision-Making
- Cognitive Engineering
- Personnel Selection/Classification
- Precision Guided Training
- Modeling and Simulation: The Human Factor
- Unmanned Air Vehicles
- Global Presence (including sustained operations and logistics)
- Biotechnology

Human Information Processing/Decision-Making

In one way or another, every Air Force function involves human information processing and decision-making. Sound decisions require the best possible total situation awareness. Therefore, a key issue is to provide the decision maker with the degree of situation awareness appropriate to the setting and circumstances. This theme addresses the intersection between computer science, psychology, and neurobiology. Ultimately, it is about the human mind, the most exciting target of research today. The objective of research in this area should be to develop a better understanding of the human decision-making process without neurobiological assists. With this understanding, more effective decisions aids can be developed.

Cognitive Engineering

Cognitive engineering refers to the need to apply knowledge related to human cognition (mental processes) to the design and operation of systems. It was invented because many

problems experienced with computerized and/or automated systems resulted from the designers overlooking these human characteristics, thus reducing the value of the system, requiring changes to costly training programs to enable the user to operate the system, increasing errors and ineffective use. Typical problems include loss of situation awareness, information overload during unforeseen events, and loss of some human skills. It is now recognized that the human needs to know what the computer is doing, why it is doing it, and what it will do next. Effective design of future automated systems, including aircraft and information systems will be greatly enhanced if effective design guidelines and principles are developed for human interaction with automated systems. Function allocation, situation awareness, seamless intervention in the event of failure. will be greatly improved as a result. In addition, improved displays, decision aids, and control systems will be possible for automated, semi-automated and manned systems for all Air Force missions and functions.

Personnel Selection and Classification

As the Air Force becomes smaller in the future, the number of inductees per year will probably be reduced by one-third compared to today. At the same time, the proficiency of performance required in many Air Force jobs will increase as Air Force systems absorb new technologies. Selecting the best recruits and placing them in the right job, a current priority, will be ever more important in the future. The right job means not only a match of cognitive and non-cognitive skills, but motivation to perform and job satisfaction. Policy plays a role here. Technological advances in assessing a recruit's knowledge, aptitude, and emotional make-up will challenge current personnel policy to be less monolithic and more flexible toward the individual, as well as allowing an extension of the selection and classification process over an airman's entire career. Thus, selection and classification are not just the doorways of entry, but a means of benevolent and informed management of Air Force personnel.

Precision Guided Training

Enormous investment is made in training, from skill instruction of inductees to flight time for combat aircraft crews. Clearly, economies will have to be made in the future while maintaining performance proficiency. New technology will make this possible, from better individual skill instruction and skill maintenance to better unit training. Intelligent tutors, adaptable to individual trainee needs and to new missions, reprogrammable quickly and inexpensively, will revolutionize the way the Air Force trains to fight.

Simulation will become a major factor in unit training. With cost a limiting factor on availability, matching the right simulation, in terms of sophistication of content and level of fidelity to the real world, to the needs of unit training is already a major challenge. Revolutionary advances in combining human factors with engineering aspects of simulation will allow exquisite tailoring of simulation to user needs at an affordable cost. Perhaps of even more importance, will be our ability to extend training technology to the training of the highest levels of force management and employment, including joint and coalition force staff training.

Modeling and Simulation: The Human Factor

Modeling of human function is essential for integration of the human into the design of new Air Force systems. The ultimate end-point of this modeling effort is fusion of the human

characteristics with the machine system characteristics into a true total human performance system. Simulation of Air Force activities encompasses everything from the simplest training devices (e.g., cockpit procedure trainers) to the most complex virtual reality systems (e.g., those designed for rehearsal of specific real-world missions). The key issue is how much simulation is enough to achieve desired training or operational objectives. The current focus of simulation technology development frequently has been improved engineering and software components, striving to attain 100% real world fidelity. While a laudable technical objective, it is not an affordable approach to future Air Force training needs. Rather, we must be concerned with the specific human uses for which the simulation is intended (i.e., achievement of specified training or performance objectives) to ensure that we procure only the fidelity and characteristics necessary. Only in this way can full benefit be achieved at acceptable cost.

Unmanned Air Vehicles

The modern battlefield, whether in the air, at sea, or on land—and even in space—is a highly lethal environment for both man and machines. It is logical, therefore, that a principal direction of the entire Department of Defense (DoD) science and technology program should be on unmanned, remotely controlled vehicles that are inexpensive to operate and replace. An example is already deployed in Bosnia, the Predator, for battlefield intelligence. It is conceivable that by 2020, technological developments will permit virtually every task currently performed by Air Force vehicles to be performed by remotely controlled vehicles. It is more likely that a mix of manned and unmanned vehicles, already upon us, is the condition for the foreseeable future. Through it all, and into the totally unmanned regime, the human will be present in one way or another to exert control. The subject at which the Air Force excels and is a world leader, human-systems interface (HSI) design, will remain central to the success of all these military systems. Technological advances will allow revolutionary changes in HSI, from better interfaces in aircraft to better information processing by human controllers of unmanned systems.

Global Presence

The Air Force projects US power all over the globe. To do that in a time of unconstrained resources is an enormous task. With resources constrained for the foreseeable future, it becomes an awesome task, fraught with vulnerabilities. Modern warfare is likely to be continuous until one combatant yields totally. Thus, the Air Force's ability to execute operations over a period of time will be critical. Sustained operations result in performance decrements from sleep-deprived fatigue and from day/night time zone change. Also, during these sustained operations, the logistical task of keeping old airplanes flying, and refitting and repairing aircraft in combat becomes even more complex. Technology can help solve both these problems with a better fatigue management system and the application of virtual reality and digital technology to visualize the solutions to logistics problems.

Global Presence also includes a discussion of chemical biological warfare considerations for the Air Force. Since the research mission for this area is assigned by Congress to the Army, the thrust of this discussion is on future capability needs to ensure airbase survivability in this unconventional warfare environment.

Biotechnology

Based on advances in the fields of biotechnology and its supporting fundamental sciences, especially neuroscience, many explosive technological changes are likely to occur in the next 25 years which will significantly impact Air Force operations and capabilities.

In the field of biology, information storage on molecules is already being researched with some success. New materials will be developed which can be doped with markers for detecting fatigue cracks, especially aircraft skins. Other materials will be adaptable to external environments for stealth and hypervelocity. By the year 2020, all aspects of chemical and biological warfare involving Air Force operations will be able to be simulated, and this simulation can be integrated into all other Air Force and joint service wargaming simulations. In addition to comprehensive simulation, other principal technological advances needed by the Air Force for successful operations in a Chemical/Biological (C/B) environment will include both agent detection (on-site and standoff), as well as decontamination of equipment and localized terrain. Personnel protective ensembles will also be compatible with mission accomplishment without degrading performance.

From the field of neuroscience, progress is being made on human brain control of machines and monitoring of workload. Neuroscience will also yield memory enhancing bioactive compounds. Commanders in the field will have a comprehensive fatigue management system for both aircrews and ground support personnel.

Biotechnology will produce a well understood, comprehensive model of human body structure and function which can then be transferred to machine design.

The point at issue is that the Air Force must be prepared to follow developments in these fields and apply them when appropriate to future role and missions.

What This Volume Does Not Include, and Why

This discussion of the future by necessity is not all inclusive. First, there are many things that we don't know and many areas where we do not have sufficient vision to predict the future; secondly, there are areas where the other military departments have primary cognizance; and thirdly, there are important areas that are more evolutionary - either in approach or impact - that are not addressed.

This volume does not consider military medical therapeutics: for example, drug and vaccine development against infectious agents and biological warfare threats, or combat casualty management. The Army and Navy share this mission. Of course, the Air Force is a beneficiary of all the extraordinary advances in the field. It is important to note that the Air Force does contribute to this field operationally in two ways: (1) surveillance of airbase personnel worldwide for disease, especially infectious disease, and (2) responsibility for air evacuation of combat casualties inter-theater and in the US. The Air Force has a modest research program on life support during air evacuation in support of this responsibility.

This volume does not consider technological advances impacting the peacetime health care system of the Air Force. This subject is really better titled "medicine in the military" to distinguish it from "military medicine" addressed in the paragraph above. Peacetime health

care in the Air Force benefits directly from the huge federal investment in medical research through the National Institute of Health.

This volume does not consider telemedicine. The Army is executive agent, but the Navy and Air Force are active participants in this Congressionally directed initiative. The technology for telemedicine is available now and is being employed. The issues in the civilian sector are principally the legal and ethical use of it, and much energy is being expended on both.

Advances in environmental protection, pollution control, and clean-up are not considered. It is true that the Air Force has environmental problems now and invests heavily in their corrections. Revolutionary advances in this field can be expected, but at present the Air Force current investment strategy is about right. There are many advances outside the Air Force, which the Air Force can apply to its benefit without mounting a massive, Air Force-funded and led effort.

Revolutionary advances in protecting of humans from various types of non-ionizing directed energy are *not* forecast. Nearly 50 years of effort on ionizing radiation protection have failed to yield significant protection. While the energy-tissue interactions are different for non-ionizing radiation vs. ionizing radiation, the experience is sobering. For non-ionizing radiation, most effort has focused on protection of the eye from lasers. Progress has been made, but agile lasers are still a threat. The only real solution is a variety of approaches to removing the eye, and the human as a whole, from exposure. For the Air Force, this means either unmanned vehicles or synthetic vision for pilots based on external sensor arrays.

Notwithstanding its title, this volume does not address the subject of biotechnology in a comprehensive way. The limited focus presented here reflects the fact that the Air Force does not need to include biotechnology in its Science & Technology (S&T) investment strategy in a major way. This may seem contradictory when one recalls the many spectacular advances in the biological sciences in the last decade. Many of these advances have been translated through biotechnology into successful products in the marketplace. The future of biotechnology is as bright as its past. But, with some specific exceptions addressed separately in this volume, future advances are going to occur whether the Air Force invests in them or not. The challenge for the Air Force is to be a smart buyer of advances funded by others: what to buy, what to tailor to Air Force needs, and when.

2.0 Human Information Processing/ Decision Making[1]

Assertion

For all Air Force weapon systems, the human will be in the control loop and must correlate, fuse and understand information for all levels of decision making (aircrew, teams, joint). This information must be presented compatible with human cognitive functions

Importance to the Air Force

Information correlation, fusion, distribution, understanding, action decisions, and result feedback will be mission essential to all future conflicts. Aircrews, commanders, joint staffs, and Commanders-in-Chief (CINC) are all in potential information overload and require tools to assist them in the information processing and decision making process.

Discussion

Current, generic models of human information processing, decision making and situation awareness exist. However, understanding cognitive processes and modeling them is underfunded. Simulations of human decision making and information processing need to be man-in-the-loop, not just constructive in nature. Development must be conducted so that constructive modeling, semi-automated forces, and man-in-the-loop simulations use a common human performance database. Additional development and testing in this area is also required.

Automation sometimes takes the pilot, commander out of control/decision loop. Advanced decision aids for all levels need to be developed and tested using human information processing principles. Advanced display technology needs to be developed and tested to support information processing, decision making, and situation awareness. Information processing and decision making have skill components and therefore need to be trained and maintained.

Enhanced mission effectiveness will result from developments in human information processing and decision making. Advanced displays designed in accordance with human factors principles will be available - real-time information for all levels of decision making.

1. For a more detailed discussion of this topic see Appendix F, Human Information Processing/Decision Making.

3.0 Cognitive Engineering[2]

Assertion

Dedicated pursuit of research in the area of Cognitive Engineering will have identified key variables and their interactions in the processing of information by humans performing all critical jobs. Systems will be designed based on this knowledge to present large quantities of integrated and fused information needed by specific users, tailored to their needs and formatted in a way that will facilitate rapid, error free processing and optimum decisions. Effective decision aids will be available to offer viable options to responsible humans. Automation will be incorporated that truly aids the user, keeping the user fully informed of status of those systems controlled, and providing the capability for the human to rapidly and effectively assume direct control, if necessary.

Importance to the Air Force

The realization of more rapid and effective information processing and decision making resulting from the application of improved cognitive knowledge will have a profound effect for all levels and activities of the Air Force. Delays and errors imposed by lack or misapplication of information will be greatly reduced. All activities dependent on the display of data will benefit. Among the more obvious improvements will be:

- Better employment of friendly forces to meet an objective.
- Fewer maintenance false removals and faster turning of aircraft.
- Accomplishment of mission objectives with fewer sorties.
- More effective training and rapid achievement of personnel qualifications.
- Qualitative improvements in the design of automated systems.

Discussion

All human activities are fundamentally based on the application of information to the task at hand. Some of the information may be intrinsic to the person, but much of it must come from outside sources. The scientific area that addresses human information processing is called cognition. Most human error is probably a result of lack of information or its faulty or untimely application. Skill in any task is largely dependent on the development of effective information processing strategies: in knowing what information is important, where it is to be found, and being able to interpret the cues or data rapidly and accurately. This is true for psychomotor activities as well as primarily mental tasks.

Past and current design practices have emphasized the development of sensor and processing systems, but have not adequately emphasized the importance of effectively transforming and communicating the data to the end user. Display improvements, for example, have generally focused on the sensory and perceptual needs of the user, but have not addressed the decision making elements. Data are often assumed to be information but in many situations,

2. For a more detailed discussion of this topic see Appendix G, Cognitive Engineering.

data must be integrated or fused to be meaningful to the user. It has generally been left to the human to provide this step and this, indeed, is one of the human's strengths. But, as activities become more complex, additional information must be processed to make a decision. Added information may delay or even increase the probability of an inappropriate decision unless effective means of integrating the information are employed. In the military context, personnel at all levels are even now inundated with data and the future promises even more. Although considerable knowledge has been acquired regarding cognitive processes, much remains to be learned and what is now known has not been implemented systematically into the design of systems.

One potential solution to the information overload problem is to automate some functions. In practice, this has generally meant the designers automated what they could, and left what they could not automate to the human. This has resulted in "clumsy automation," which increases the problems of the human if unanticipated events arise or if a failureoccurs. A better alternative may be to determine what can be done to increase the ease, accuracy, and speed of human information processing, in order to make information interpretation more "intuitive" than current systems allow. The ability to do this depends on our understanding of human information processing variables and laws. Then we must apply this knowledge to the design of information systems in a much more systematic manner and with a higher priority than has been characteristic of past practice.

4.0 Personnel Selection and Classification[3]

Assertion

Significant improvements in the system for selecting and classifying personnel will be developed by 2020. The system will involve a refinement and expansion of measures of the various cognitive factors that are related to success both in training and in operational performance. Present selection and classification (S&C) systems rely largely on such cognitive factor measures, but capture only 15-25% of the criterion variance in training and mission performance. The S&C system of 2020 will allow an effective inclusion of a variety of non-cognitive factors as well, such as personality and motivation. The result will be a more precise means of evaluating trainee capabilities and potential, one that will be a significant enabling technology for precision guided training and more effective personnel and force management.

Importance to the Air Force

Selection and classification are the first functional steps in Air Force service or careers after the initial recruitment. S&C seeks to determine the "shape" of the recruit "peg" and to place the right "pegs" in the right "holes." To the extent that the S&C process is imprecise, we have potential waste of human, material, and financial resources. But, more importantly, we run a significant risk of degraded operational mission performance due to malfits, misfits, and force-fits of persons, training, and jobs.

- Potential benefits of an improved S&C system include:
- Training production "waste" reduced
  - Cost savings
  - Time savings
- Mission/Job performance increased
  - Square pegs in square holes
- Career/job satisfaction and enhancement

Discussion

The management of its personnel resources is one of the most important functions - arguably the most important - that the Air Force performs. Without the optimal combination of people, equipment, and management, the weapon systems will not perform in the manner desired. While we may never achieve perfection in the S&C process, there is room and promise for significant increases in S&C efficiency and effectiveness. The scientific underpinning of effective S&C is rooted largely in the areas of cognitive and non-cognitive psychological functions and their relationship to learning and human performance. Research progress is being made at both the theoretical and applied levels, and such efforts must continue to be supported and receive priority. Research being performed on brain function, for example, offers exciting

3. For a more detailed discussion of this topic see Appendix H, Personnel Selection and Classification.

possibilities for both our theoretical understanding of human performance and for use in S&C systems in the future. As the Air Force downsizes, more effective use of its personnel resources is mandatory. A more precisely targeted S&C system will be an important step in meeting that requirement.

5.0 Precision Guided Training[4]

Assertion

By the year 2020, utilizing knowledge of human learner characteristics and their interactions with content to be learned and presentation methods, it will be possible to increase significantly both the effectiveness and efficiency of Air Force training. The approach, labeled Precision Guided Training (PGT), will involve a tailoring of training systems, programs, and outcomes to the wide range of individual differences and capabilities that exist among trainees, as well as to validated models of human cognition and learning. It will allow for the first time a truly interactive, individualized integration of trainee and training systems.

Importance to the Air Force

Training is not only the *sine qua non* of all Air Force capabilities and operations, it is one of the largest consumers of Air Force budget resources. Optimal utilization of training technology that will be available in 2020 will produce not only significant cost benefits, it will produce significant increases in operational readiness and mission performance.

- Potential benefits include:
- Training cost reductions up to 50%
- Training time reductions up to 30%
  - Less time away from unit
  - Increased career productivity
- Mission performance increases up to 30%
  - Increased individual/unit proficiency
  - All levels of skills trained and exercised
  - Increased readiness through timely training
  - Capability to train for joint/coalition operations
- Better utilization of Air Force resources
  - Human resources
  - Others (aircraft, flying hours, ranges, etc.)

Discussion

Present day training is relatively inflexible in its ability to recognize and adjust to the wide range of individual differences that exist among trainees. Our "one-size-fits-all" training, of necessity, largely ignores differences in trainee background, learning styles, intellectual structure, and a variety of other factors that affect the benefits individuals derive from their

4. For a more detailed discussion of this topic see Appendix I, Precision Guided Training.

instructional experiences. Tailoring instruction to the individual can significantly increase the effectiveness and efficiency of the training regimen. It will be possible by 2020 to combine three converging human-related technologies to produce training that recognizes such individual differences and that is much more precisely targeted in its production of trainees who will possess those job skills and human characteristics required for the highest levels of mission performance. The three technologies that will allow such tailoring are:

1. Personnel selection and classification systems
2. Cognitive and non-cognitive models of the human learner and of the instructional process
3. Computer technology to support training simulations, training equipment, and training management systems.

The merging of these technologies will allow development of individualized training that is precisely tailored to the particular capabilities and needs of the individual trainee as well as to the skills, knowledge, and attitudes required for successful job and mission performance. The concept of selective fidelity in the design of training devices (i.e., only procure the fidelity and functional features necessary to produce the *desired training outcomes*), in combination with the order of magnitude decreases in computer cost and increases in computer capability, will make effective training devices affordable and available on a wide scale. This will allow the bulk of training to be accomplished at the home unit. In addition, it will be possible, through distributed interactive simulation, to have effective training of all levels of skills, varying from the individual, to unit, to joint force levels.

Precision guided training offers a means for significant leveraging of the mission effectiveness of Air Force systems. Given support for the necessary science and technology advances required for PGT (cognitive psychology, modeling of human cognition and learning, and continued advances in the computer capability/cost function), the capability will exist to achieve training and operational benefits of the type and magnitude described here.

6.0 Modeling and Simulation: The Human Factor[5]

Assertion

By the year 2020, all issues currently surrounding the difficulties and challenges of modeling or simulating (or even understanding) human behaviors, functions, performance, memory, thought and decision processes, the factors that affect them and the impact of these on the outcome of military objectives, will have been overcome by taking a new approach to integrating these factors into our machines and computer systems designs.

In future advanced systems, the human/machine interface will no longer be an issue because the human and the machine will be merged into a unified stand-alone system, where the whole is greater than the sum of the parts, and the constraints previously imposed on the system by the interfaces will no longer inhibit full performance at theoretical limits. This capability will not only allow dramatically increased effectiveness in high performance aircraft and spacecraft of the future, but will lead to more effective operations of remotely piloted vehicles.

Importance to the Air Force

Our models, simulations, and simulators compose a segment of the DoD analysis and training toolkit, and as such are relied upon heavily as cost effective aids to assist planners, operators, trainers and decision makers. These tools are used to support military decisions that affect outcomes, e.g., force sizing, mission planning, human resource planning, weapon procurement, wartime operations, logistics planning, and national policy analysis.

Seamless operating, training, and mission planning/mission rehearsal systems will replace large fixed-base training systems (domes, flight simulators). Many of the new training ranges and battlegrounds will likely reside on the internet in cyberspace. The end result of these technological advances will be more portable training and mission planning/rehearsal systems and reduced cost of keeping a plethora of diverse hardware and software systems current.

Discussion

Although there is a solid base of human performance modeling technology and data which can provide required input to combat simulations, human performance factors are not adequately incorporated into the construction of models and simulations to allow those factors to be taken into consideration by the model as it generates information for decision makers. The focus must be both on including human behavior and performance as inputs to the models and simulations, and on obtaining, quantifying, and processing the human performance data so that they can be used in these models.

Human performance is a variable, without question, but is not always treated as such, primarily because it has been so difficult to do so. To what extent existing combat models can accept or be modified to accept near-term human performance factor (HPF) data bases and provide HPF-influenced output for support of decision issues must be addressed. Only then can

5. For a more detailed discussion of this topic see Appendix J, Modeling and Simulation: The Human Factor.

a reasonable case be made to modify existing models or to start over with something new, built with the integration of HPF as appropriate variables in the models.

With renewed emphasis on those missions and contingencies at the lower levels of conflict, but with a higher likelihood of occurrence (e.g., drug interdiction, peacekeeping, low and mid-intensity conflict), this increased emphasis on a diversity of operations requires a significant augmentation of human behaviors and human performance factors data for incorporation into these new models. New models and simulations are needed for political, economic, ethnic, and religious effects on international security and their interactions with military effects and each other. Focus on new types of combat models should be placed on higher level human performance factors (e.g., leadership, cohesion, and benefits of warfighting experience and training), to the extent that they may affect battle outcome.

At the level of complexity and sophistication demanded by Air Force missions, the applications of new technologies will be required to enable the complete integration of the human and his machines into a new kind of seamless hybrid system (the next generation "virtual reality" systems), without interfaces as we know them today. To achieve these goals, the notion of "interface" will have to be supplanted by the concept of "human/machine integration." Integration in this sense, means that the operator and the machine will become one functioning entity, similar to the notion of the "cyborg warrior." In this future world, the warfighter enters the cockpit, where there are no obvious controls or displays. As he sits down, his chair recognizes him and begins to metamorphose, to wrap around him, becoming his g-suit, Heads-up Display, flight controls, weapon systems and communication controls, vital sign monitors, and ejection seat. Enhanced EEG receptors attach to permit the warfighter to merely think of an action and the system will execute his mental instructions.

7.0 Unmanned Air Vehicles[6]

Assertion

Extrapolating from today's state-of-the-art, it is anticipated that the technology will exist by the year 2020 to field a force of unmanned vehicles capable of accomplishing most of the tasks being performed by today's Air Force. In light of emerging technological developments and evolving mission roles, the Air Force must look beyond the next 25 years of piloted aircraft operation and begin now to direct attention toward the research needed to define and optimize the role of the human in unmanned system operation. An effective user interface for these systems will allow the user to seamlessly move back and forth along the continuum from remote manual control to fully autonomous systems.

Importance to the Air Force

Properly used, remotely controlled vehicles can serve as force multipliers by increasing the lethality of friendly forces and reducing vulnerability to enemy forces. With the availability of this operational potential, the need to place the aircrew directly in harm's way can be significantly reduced.

- Potential applications of unmanned vehicles include:
- Intelligence gathering and reconnaissance
  - Small units (e.g., robotic birds/bees)
  - Miniature UAV target detectors/hunters/and trackers
  - Larger Tier 1, Tier 2, and Tier 3 UAVs for sophisticated reconnaissance and surveillance
- Mobility and airlift support
  - Precision delivery with option to control delivery from the ground destination point
- Weapon delivery against ground, sea, air, and space targets
- Achievement of air superiority
  - Unmanned air combat vehicles with close-in combat maneuvering and beyond visual range tactical capabilities
  - UAV wingmen for support of piloted aircraft
  - Multi-ship UAV combat

Discussion

Information display systems and concepts designed for piloted aircraft are not necessarily the most effective for the remote control and operational utilization of UAVs. The optimal

6. For a more detailed discussion of this topic see Appendix K, Unmanned Air Vehicles.

display system for the remote controller may be quite different than that required when control resides in the cockpit of a manned aircraft. The idea of creating a "virtual reality" for the human controller, transparent to the mode of operation, wherein the human/machine interface is the same whether the human is in the cockpit or in a remote location is an intriguing one. In reality, however, optimization of the vehicular interface may require that a very different set of psychomotor and perceptual relationships be established to optimize control in the different situations. As an example of our concern, flight simulators which receive the highest marks for realism from experienced pilots also score the highest on the incidence of simulator sickness. Locomotor ataxia, interference with higher order motor control, physiological discomfort, and visual aftereffects have been reported.

Introducing aids to vehicular control in the form of automation has been found to eliminate some tasks, but creates new ones associated with programming, engaging, disengaging, etc. Loss of "situation awareness" also has been found to be a very real possibility if the human operator is not actively in control of the vehicle or if the operator's attention is diverted from continuously monitoring the present state of the vehicle.

A dedicated effort is required within the Air Force in order to resolve these and related issues in order to optimize the human role in the operation of unmanned systems.

8.0 Global Presence (Sustained Operations)[7]

Assertion

By the year 2020, advances in fatigue management will allow a two to three fold increase in duty-time. These advances will keep individuals alert and effective for two-three days at time, either non-stop, or by managing sleep patterns. The result will be a capability to launch aircrews from US bases who will be prepared to fight on arrival.

Importance to the Air Force

An effective fatigue management system will lead to quicker power projection and use by allowing crews to fight immediately even after a long mission to reach the fight point. Fatigue management will also result in increased crew effectiveness around the clock and thus safer night operations. Better fatigue management will lead to two approaches to increased sortie generation capability. First, fewer crews will be required to cover initial mission requirements. Conversely, the same number of crews used today can now cover many more missions. Both approaches have the additional advantage of reducing the deployment footprint relative to the number of sorties.

Discussion

The field of fatigue management, and circadian rhythm desynchronization, is becoming more mature. New chemical compounds to sedate/arouse personnel are under development which have far fewer side effects. Biologically natural compounds have the potential to assist in this area. Better metrics of effect and efficacy have been developed and are available for use.

Further effort needs to be made in several areas in order to ensure a fatigue management system is available for widespread use by 2020. The use of existing compounds should be further refined. Optimal sleep hygiene/training techniques need to be developed and taught to aircrews. Further metrics to measure effect and efficacy should be implemented and tested. A better understanding of fatigue and its components, a quantification of sleep effects and specific mechanisms of action are required. In addition, new chemical compounds tailored to counteract specific adverse effects of fatigue must be developed, tested, and fielded for general use.

The main hurdles to this effort are a lack of basic knowledge on fatigue, sleep, and circadian rhythms, and biomolecule development technology. Actions needed are:

- Encourage consistent use of existing drugs and fatigue management techniques in the field.
- Focus on a basic sleep research program to prepare for the future with a goal of fielding a comprehensive fatigue management system for commander's use by 2020.

7. For a more detailed discussion of this topic see Appendix L, Global Presence, p. L-1.

9.0 Global Presence (Logistics)[8]

Assertion

By 2020, information on design, support, and modifications to weapons systems will be available and plentiful in digital format. The human-centered aspects of operation and maintenance will be included in simulations and electronically available. Technology, especially techniques and tools for visualizing processes and human actions, will allow this simulation capability to extend to all other logistics processes. Using computer graphics and virtual reality devices, we will be able to simulate the flow of material, maintenance and repair, and logistics command and control real time.

Importance to the Air Force

Logistics support is a major cost of Air Force ownership of weapon systems. The majority of these costs are human-centered. The application of visualization technology for logistics will reduce the cost of maintenance manpower, technical data, and training. Similarly the deployment footprint can be reduced by limiting the need for people, equipment, and parts at forward locations. The end result is better logistics planning, command, and control.

Discussion

Scientific visualization has become an important tool for most engineering domains. Computer-aided design (CAD) tools already permit realistic 3-D imaging of product geometry and seamless integration of engineering analysis and manufacturing data. Computer graphics workstations generate compelling visual displays that aid scientists in understanding molecular structures, help statisticians understand complex data relationships, help architects explain their designs, and so on. With the aid of computer animation, 3-D data definition, and various rendering techniques, realistic simulations of many different products can be created to support engineering design and product prototyping.

This visualization paradigm will add a new dimension to logistics simulation and automation. Electronic mock-ups, using animated 3-D graphics and virtual reality interfaces, will promote a concurrent engineering role for human-centered aspects of system support. It will be possible to visualize critical maintenance and repair tasks, detect and correct sources of human error, and generate maintenance instructions (tech manuals, job aids, etc.) automatically from the CAD screen. Digital design archives will allow human-centered system support elements to be reviewed and verified when systems or subsystems are modified.

With emerging technologies, analysts and users can enter, navigate, and manipulate a CAD virtual world. It will be possible to verify critical equipment operation and maintenance tasks by allowing real people to work with virtual tools in virtual work spaces. Task analysis supported by these technologies will have many human-centered applications. It will be possible to describe job/task ability requirements, to specify tool and support equipment needs, and to identify safety problems. More importantly, design changes can be made to accommodate human limitations and capabilities and the result viewed on the screen. With associated advances

8. For a more detailed discussion of this topic see Appendix L, Global Presence, p. L-5.

in natural language processing, maintenance instructions will be generated automatically. Combining these instructions with CAD graphics of human forms will make automatic generation of electronic technical manuals feasible.

Visualization technology will permit operational logistics issues to be modeled with greater realism and larger consequence than they ever have before. For example, the movement of military material through aerial ports might be simulated graphically to identify bottlenecks, optimize warehouse space and resource utilization, and manage air and ground transportation scheduling. Logistics command and control centers might have real time pictures of the status of critical cargo in transit, port and depot operation, and airlifter location across the globe. Managing these assets more effectively would have force multiplying effects. Making 3-D animated visuals available for training simulation of logistics management war skills would leverage training dollars.

Distributed interactive simulation will allow logistics assets and processes to participate directly in wargames for training and readiness assessment and in virtual prototyping for new/altered systems. New concepts for aerospace ground equipment could be tested on the same electronic air/land battlefield used to evaluate new fighter weapons or tactics. Visualization is a critical feature of the virtual prototyping approach advocated for concept evaluation and defense acquisition decision support.

The hurdles to reaching this model of future logistics include a lack of definition and standardization criteria for human problem-solving/decision-making, the application of this knowledge in an integrated fashion to the display concepts, and the development of software to function in a human-centered approach to logistics command and control.

On the other hand, the benefits of reaching this standard of logistics operation is threefold. From an affordability aspect, reduced system development and ownership costs are possible due to early design evaluation and incorporation of logistic support options. Deployability will be enhanced by reducing the number of pallets moved (total and per unit). Finally, better logistics planning will lead to logistics support tailored to specific needs.

10.0 Biotechnology[9]

Assertion

By the year 2020, biotechnology and the supporting fundamental sciences, especially the neurosciences, will have produced an array of advances which will extend human performance in time and proficiency so as to meet the needs of the intense, sustained conflicts of the future. These advances will also offer to materials scientists and structural engineers novel concepts for new materials and new structures, and even new materials that greatly extend the range of properties in terms of durability, flexibility, low observability, and adaptability to changes in the surrounding environment.

Importance to the Air Force

Reduced manpower within the Air Force is a certain trend for the future, making the most efficient use of available manpower an absolute imperative. Advances in biology will greatly increase the opportunities for the Air Force to do just that. For example, science will extend the hours of personnel alertness, adjust information displays to match user workload and attentiveness, and improve the situation awareness of personnel at all levels through improved memory.

Discussion

Achievements today in biological research relevant to Air Force missions are clear indicators of achievements to come, many by the year 2020.

- Present-day discovery of specific receptors in the brain involved in short-term memory, the possibility that these are compromised in Alzheimer's disease with loss of memory, and the further possibility that specific compounds will be constructed through new medicinal chemistry strategies to reverse this memory loss, all suggest eventual availability of compounds which to a degree will potentiate memory in normal individuals.
- Present-day enhanced electroencephalograph (EEG) with a 128 sensor array (clinical EEGs have less than 20) is already configured in a skullcap easily worn by a computer operator so that brain wave patterns detected by the EEG at specific frequencies can be employed as signals to begin to influence information content and display designs on a computer screen. A logical extension of this research achievement, which required 20 years of research, is to couple the human operator with the machine to maximize human operator performance, which will maximize machine performance as well.
- The EEG is already being used to detect the brain wave patterns at specific frequencies that represent the thought to take an action before the action is actually taken. The work presages the time in the future when a human can think an action and have that action performed automatically by a machine ("no-hands control").

9. For a more detailed discussion of this topic see Appendix M, Biotechnology.

- Human body structure/function modeling will be largely understood by 2020, whereas today the modeling of dynamic activity, such as pilot ejection - a very complex cluster of forces involving the human body and the environmental extremes into which it is being propelled - is very incomplete. Success in this overall effort will greatly enhance the system design process, thereby eliminating costly design revisions due to poorly functioning human/system interfaces.

- Molecular optical information storage is almost a reality today with the fusion of DNA with silicon into a true biochip. The shift of DNA analysis from wet chemistry to dry processes (optical interrogation) will convert this biochip into the next generation of computer: the optical computer with computational powers many orders of magnitude greater than present computers.

- Material scientists and structural engineers are beginning to recognize value in the study of biological materials and their hierarchical structure. Nature does the most extraordinary things with a very small number of elements. These elements are assembled into structures that have capabilities which often exceed those of synthetic structures, for example, flexibility, yet toughness, and injury tolerance, even self-repair. Harnessing the underlying concepts of these natural phenomena will produce a new generation of materials and structures that could transform air vehicle performance in the future.

11.0 Concluding Commentary: Payoffs and Recommendations

Payoffs

The topics covered in this volume are all oriented toward one fundamental objective, maximizing operational effectiveness in accomplishing the assigned roles and missions of the Air Force in the year 2020 and beyond. In achieving this objective two factors are of paramount importance:

- Performance improvement
- Reduction in cost of mission operations

Performance improvement has many faces: information gathering, processing and decision making, accuracy of weapons delivery, management of forces, work station design, and training, to name only a few. Perhaps the area of research offering the greatest performance payoff lies in obtaining a better understanding of human information processing and decision making. A subset of this high payoff area lies in understanding the mental processes such as reasoning and memory that are important in achieving and maintaining "situation awareness." Information correlation, fusion, distribution, understanding, action decisions and result feedback will be mission-essential to all future conflicts. Even today, pilots, commanders, joint staffs, and Commanders-in-Chief are all in potential information overload and require tools to assist them in the information processing and decision making process. The situation will become even more demanding in the future as the technologies of war proliferate and threats increase. Furthermore, 25 or more years from now when every potential adversary has fast information processing capabilities and sophisticated decision aids, our advantage in this field will shrink. Our advantage is a moving shadow. The width of that shadow is the measure of our winning potential.

Other areas with the potential for high performance payoffs in future operations include:

- Reduction in personnel fatigue at all levels through drug and other strategies for better sleep and circadian rhythm control.
- Improved airbase survivability in a chemical/biological warfare environment through better personnel protection, tailored to Air Force needs, better training, and better simulation of the threat.

Reduction in cost of mission operations is the objective of much of the Air Force S&T investment. Where among the topics covered in this volume can significant reductions in cost be achieved? One area in particular is logistics. Improvements in logistics are achieved incrementally. They rarely "knock your socks off" with their brilliance, but the potential for leveraged gain is enormous. The logistics system of the Air Force is so huge, and the cost of maintaining an aging fleet of aircraft so certain to rise, that dollars saved multiply instantly into millions, even billions. How much saved, where? Every effort must be made to capture the data so that we will know the answer. Not every approach in logistics will pay off. Choices still have to be made. They must be smart choices. The overarching consideration is that all choices be human-centered.

There are two other topics in this volume which contribute in major ways to cost reduction:

- Unoccupied air vehicles
- Training, individual and unit

The cost savings of UAVs are obvious: in aircraft and lives. UAVs, tailored to the mission, are much cheaper to build, maintain, and replace. Aircrew lives are saved by keeping them out of harm's way—UAVs go close in, maneuvering as no occupied aircraft can. On-board sensors and off-board controllers ("pilots") will deliver the payload on target, whether ordnance or supplies.

Training is currently, and will continue to be, a very significant item in the Air Force budget. The cost savings just waiting to be achieved in training are pretty obvious. Mostly these savings are measured in terms of reduced time to achieve a training result. But there are other very important savings to be had, too—in the cost of training devices and facilities. Set aside the explosive issue of simulator training replacing some flight hours and the alleged savings. Design of training simulators only to the level of complexity required for the training result will reap huge savings.

Cost reductions in training through reduced training time will be achieved mainly in individual skills instruction. Quantitative estimates of savings from introduction of new approaches to training at all levels are potentially enormous.

Recommendations

1. The simple overarching message in this volume is that Air Force leadership must declare as the first principle that all Air Force systems are, and will be designed in the future as, human-centered systems. This declaration means that systems maintainers and developers cannot, as now, cut human-in-the-loop considerations first and engineering considerations last.

2. Advances in human information processing/decision making depend on a better understanding of human cognitive processes and the influence of non-cognitive factors on them. That understanding translates into a commitment to a consistent level of investment in cognitive science research and a requirement of cognitive scientists that they produce some incremental products from their research.

3. Advances in testing and profiling human capabilities will make it possible to find exceptionally capable individuals and match them to the most mission-critical positions. Personnel management must then recognize the inevitability of these advances and begin the process of adjusting long-standing personnel policies to accommodate these advances. Our potential adversaries will do this, and we must.

4. Advances in training technology will deliver the capability for precision guided training. The Air Force must buy advanced training as it becomes available, and maintain its cadre of in-house training technologists who can tell acquisition leadership what to buy and what to avoid.

5. Advances in simulation technologies, such as the ability to create virtual worlds will dazzle potential users. The degree of realism desired for entertainment and the degree of realism needed for training, however, are not necessarily the same. The Air Force must establish as acquisition policy that simulators and other training equipment will provide the level of fidelity required for cost-effective training and no more. In implementing this policy, it is essential that valid criteria be established to measure training effectiveness and thereby provide a basis against which the cost effectiveness of training aids and devices can be evaluated.

6. Engineering advances in unoccupied air vehicles will lead eventually to replacement of all occupied combat aircraft by UAVs. Air Force leadership must require the Air Force S&T program to define the level at which human control will be exercised and the specification of the human-system interface that will exercise this control.

7. Advances in logistics management in industry, as well as in the DoD, will move in the direction of totally integrated comprehensive systems for each corporate entity, and eventually for whole industries. DoD and the Air Force have already espoused this principle, but now must declare that it will be implemented with every choice being made so as to place the human operator/user at the center.

8. Advances in biology will produce new strategies for creating new materials, designing new structures, manufacturing new end-products. The Secretary of the Air Force must assign to a senior biologist of the Air Force, the responsibility for ensuring that these advances are being integrated at the right time and in appropriate ways into the Air Force S&T program.

9. Advances in biology and medicine will produce new strategies for enhancing human performance and limiting performance decrement. The Secretary of the Air Force must assign to a senior biomedical research physician in the Air Force,the responsibility for ensuring that these advances are being integrated at the right time and in appropriate ways into the Air Force S&T and personnel management programs, exercised through both command and Surgeon General channels.

10. Air Force leadership must invest in the psychological, biological and computer sciences sufficient to force the frontiers of these sciences forward in areas where the Air Force benefits. Diverse as these sciences are, they fuse in support of the vision presented here. To convert advances in these sciences to practical Air Force applications, Air Force leadership must also invest systematically and long term in the development of enabling technologies based on these sciences, technologies repeatedly identified in this volume. These technologies include but are not limited to human modeling, both cognitive and physiological, workload and fatigue management systems, personnel assessment instruments, precision guided training, distributed interactive simulation for training, and information management responsive to human cognitive processes.

Appendix A

Charter for Human Systems/Biotechnology Panel New World Vistas Study

The Human Systems/Biotechnology Panel was chartered to develop concepts and ideas for those topics that reflect the role of the human in Air Force weapon systems. The panel members are composed of industry and academic experts with experience in the fields of psychology, training, modeling and simulation, and chemical/biological warfare.

The panel's basic premise is there are no unmanned systems; the human will always remain critical to the operation and sustainment of Air Force missions. This research includes issues related to training (aircrew and technical), selection and classification of personnel, sustained operations (fatigue, circadian rhythms, logistics), the role of remotely controlled vehicles, and improved situation awareness and decision making. Research in the biotechnology/biology fields are the mission of the Army and Navy and the panel will only briefly cover those areas that are critical to the Air Force.

In addition, the panel was asked to consider issues related to affordability, dual use, and joint operations. The panel was to look at the charter of the Scientific Advisory Board and the structure and mission of the Air Force laboratories.

Appendix B

Panel Members and Affiliations

SAB Members

Dr. Garrison Rapmund, Chairman
Maj Gen, US Army Retired
Independent Consultant

Dr. Richard Gabriel
Independent Consultant

Dr. Henry Taylor
Director, Institute of Aviation
University of Illinois

Dr. Harry Wolbers
Independent Consultant
Organizational and Engineering Psychology

Ad Hoc Advisors

Dr. Wallace Prophet
Independent Consultant

Dr. Adelia Ritchie
Vice President
Scientific Research Corporation

Dr. William Welch
Independent Consultant

Participant

Dr. Christopher Wickens
Professor of Psychology
University of Illinois

Executive Officers

Captain Teresa Quick
Armstrong Laboratory
Brooks AFB

Major Michael Reagan
Executive Officer
USAF Scientific Advisory Board

Technical Editor

Captain Sandra Eisenhut
Professor of Psychology
USAF Academy

Appendix C

Panel Meeting Locations and Topics

14-16 Mar 95 Brooks AFB, TX

Human Resources

24-27 Apr 95 Wright-Patterson AFB, OH

Logistics Research
Crew Systems

3-5 May 95 Maxwell AFB, AL

Training
Human Systems

Appendix D

List of Acronyms

Acronym	Definition
AETC	Air Training and Education Command
AFB	Air Force Base
AL	Armstrong Laboratory
AMPA	Type of Glutamate Receptor
AWACS	Airborne Warning, Alert, and Control System
BAC	Brain Activated Control
CAD	Computer Aided Design
C/B	Chemical/Biological
C^4I	Command, Control, Communications, Computers and Information
CRT	Cathode Ray Tube
DIS	Distributed Interactive Simulation
DNA	Deoxyribonucleic Acid
DoD	Department of Defense
DSI	Distributed Simulation Internet
EEG	Electroencephalograph
FMS	Flight Management System
HMD	Helmet (or Head) Mounted Display
HPF	Human Performance Factor
HSI	Human System Interface
HST	Human Systems Technology
IMIS	Integrated Maintenance Information System
ISD	Instructional Systems Development
NCA	National Command Authority
PC	Personal Computer
PGT	Precision Guided Training
R&D	Research And Development
S&C	Selection and Classification

S&T	Science and Technology
SA	Situation Awareness
SAB	Scientific Advisory Board
TMS	Training Management System
UAV	Unmanned Aerial Vehicles
US	United States
VR	Virtual Reality

Appendix E

List of Contributors

Many individuals assisted the panel with information, some with specially prepared reports, some with published articles and unpublished manuscripts, and some with presentations and informal discussions. Their contributions are most gratefully acknowledged.

Professor Ilhan A. Aksay
Director, Princeton Materials Institute
Princeton University
New materials and structures

Professor Eric Baer
Department of Macromolecular Science
Case Western Reserve University
New sensors for structures

William O. Berry, PhD
Director, Life and Chemical Sciences
Air Force Office of Scientific Research
Neuroscience

Gene D. Block, PhD
Director, Center for Biological Timings
University of Virginia
Sustained operations (fatigue)

David R. Boone, PhD
Department of Environmental Science and Engineering
Oregon Graduate Institute of Science and Technology
Unusual microbial ecology

James H. Brown, PhD
Directorate of Biological Sciences
National Science Foundation
Future biological science

Jim C.I. Chang, PhD
Director, Aerospace and Materials Science
Air Force Office of Scientific Research
New materials and structures

Bertram Cream
Human Resources Directorate
Armstrong Laboratory
Sustained operations (logistics)

Professor Eugene E. Covert
T. Wilson Professor of Aeronautics
Massachusetts Institute of Technology
Cognitive engineering

Andrew Crowson, PhD
Director, Materials Science Division
Army Research Office
New materials and structures

Charles A Czeisler, PhD, MD
Director, Laboratory for Circadian and Sleep Disorder Medicine
Harvard Medical School
Sustained operations (fatigue)

David F. Dinges, PhD
Co-Director, Unit for Experimental Psychiatry
University of Pennsylvania Hospital
Sustained operations (fatigue)

Dak M. Edgar, PhD
Sleep and Circadian Neurobiology Laboratory
Stanford University School of Medicine
Sustained operations (fatigue)

Alan Gevins
President, SAM Technology, Inc.
San Francisco, CA
Electroencephalography

Professor Richard Granger
Center for the Neurobiology of Learning and Memory
University of California, Irvine
Memory

Darryl P. Greenwood, PhD
Chief Scientist
Rome Laboratory
Molecular/optical data storage

Genevieve M. Haddad, PhD
Life and Chemical Sciences Directorate
Air Force Office of Scientific Research
Neuroscience

Frederick L. Hedberg, PhD
Life and Chemical Sciences Directorate
Air Force Office of Scientific Research
Biomimetics/new materials

Michael J. Heller, PhD
Vice President, Research
Nanotronics, Inc.
San Diego, CA
Molecular/optical data storage

Gilbert G. Kuperman
Crew Systems Directorate
Armstrong Laboratory
Human factors of automated target detection

Professor Roderic Lakes
Department of Biomedical and Mechanical Engineering
University of Iowa
New materials and structures

Professor Richard A. Lutz
Director, Center for Deep Sea Ecology and Biotechnology
Rutgers University
Unusual microbial ecology

Professor Gary Lynch
Center of Neurobiology of Learning and Memory
University of California, Irvine
Memory

Wayne Martin, PhD
Crew Systems Directorate
Armstrong Laboratory
Human/machine interface

Edwin May, PhD
Science Applications International Corporation
Palo Alto, CA
Physics of consciousness

Grant R. McMillan, PhD
Crew Systems Directorate
Armstrong Laboratory
Brain control of machines

Robert Y. Moore, MD, PhD
Director, Center for Neuroscience
University of Pittsburgh
Sustained operations (fatigue)

Louise A. Obergefell, PhD
Crew Systems Directorate
Armstrong Laboratory
Human body modeling

J. Wesley Regian, PhD
Human Resources Directorate
Armstrong Laboratory
Personnel classification

Clyde Replogle, PhD
Crew Systems Directorate
Armstrong Laboratory
Chemical/biological warfare

Professor Mehmet Sarikaya
Department of Materials Science and Engineering
University of Washington
New materials and structures

Linda Sawin, PhD
Human Resources Directorate
Armstrong Laboratory
Personnel selection

Howard R. Schlossberg, PhD
Physics and Electronics Directorate
Air Force Office of Scientific Research
Optics

Joel M. Schnur, PhD
Director, Center for Biomolecular Science and Engineering
Naval Research Laboratory
New structures

Valerie Shute, PhD
Human Resources Directorate
Armstrong Laboratory
Intelligent tutor training

L. Jocelyn West, MD
Director Emeritus, Neuropsychiatric Institute
University of California, Los Angeles
School of Medicine
Behavioral biology

Professor Christopher D. Wickens
Institute of Aviation
University of Illinois
Situational awareness

Glenn F. Wilson, PhD
Crew Systems Directorate
Armstrong Laboratory
Electroencephalograph workload monitoring

F. Eugene Yates, MD
ALZA Corporation
Palo Alto, CA
New drug delivery systems

Appendix F

Human Information Processing/Decision Making

We assume for the year 2020 that, even with the advent of Unmanned Air Vehicles (UAVs) for some Air Force missions, the human will continue to be involved in the operational *control* of Air Force weapon systems. Air Force systems will be either manned by persons on board, or for UAVs, humans will be required to control the vehicles from remote locations. This topic will be covered in more detail in Appendix K, Unmanned Air Vehicles. For all weapons systems to which the human is assigned, whether on board or remote, a large amount of information must be processed. Information pertaining to the operation of their own vehicle, the external environment, enemy aircraft and UAVs, ground forces (both friendly and unfriendly), wingmen and other events and objects must be perceived and interpreted. The information must be responded to immediately, ignored, or stored in memory for later action. In the year 2020, there should be a choice of where and how the information will be stored, how it will be accessed and how it will be used in real time decision making. According to human information processing theory, information not immediately used for action, will be stored in long-term memory. In 2020, technology will be available to store the information in a database for later access for computer decision aiding and action. It will be important if the system is manned to keep the human in the "knowledge/control" loop if the pilot is going to be involved actively in the decision making and action process.

A Model of Human Information Processing

Models of human information processing have been developed from basic stimulus-organism-response psychological theory. A basic assumption of these models is that a series of stages or mental operations occur within the brain between the input of stimuli and the output of responses. Figure F-1 illustrates a typical four-stage human information processing model.[1]

The first stage in the model is *sensory processing*. An assumption of this processing stage is that there is a separate sensory store for each sense modality. For the visual modality, physical energy (light) is converted to electrical energy (neural response of rods and cones in the eye). During the second stage, *pattern recognition*, electrical energy is integrated into meaningful elements. This important stage of information processing is the least understood of the four stages but it is known that the pattern recognition process involves integrating the electrical energy from the sensory store into semantic or meaningful codes from *long-term memory*. This perceptual process may be limited by the amount of available *attention resources*. Perceived information may be temporarily stored in working memory or related directly to the third stage, *decision and response selection*. The supply of attention resources can also limit the decision and response selection process. One can easily see that there are a number of options during this stage. The information can be stored in long-term memory for much later action; it can be temporarily stored in working memory for delayed action; it can be integrated with other information from working memory and/or long-term memory during the decision process or a

1. Wickens, C. D. & Flach, J. M. (1988). Information Processing. In E.L. Wiener & D.C. Nagel (Eds.), Human Factors in Aviation (pp.111-155). San Diego, CA: Academic Press.

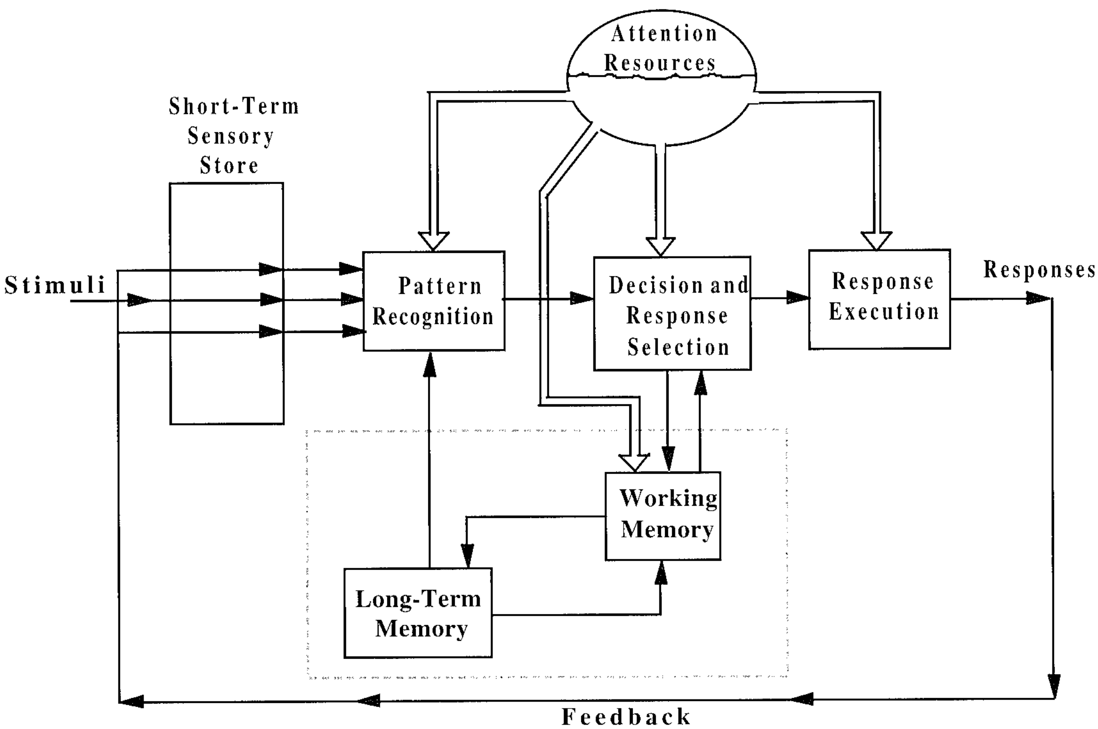

Figure F-1. Human Information Processing Model

response may be selected immediately. During this stage the human skeletal/muscular system is activated to carry out the selected action and a feedback loop is in continuous activation to provide a coordinated response. It is assumed that potential costs and benefits of the options are considered during the decision process. The final stage involves *response execution*. The responses typically provide input to the senses by way of a feedback loop which may serve as inputs relevant to selecting following responses.

To further decompose these stages, the perceptual stage (pattern recognition) of information processing involves the following two processes: signal detection and information selection.

Signal Detection

According to signal detection theory, there are four outcomes from each signal detection task:

1. A signal can be present and the human can detect it (HIT)
2. A signal can be present and the human can fail to detect it (MISS)
3. The human can detect a signal that is not present (FALSE ALARM)
4. The human can correctly observe that no signal is present (CORRECT REJECTION)

The probability of each of these outcomes is a function of *sensitivity*, a ratio of the human's ability to distinguish a signal from noise, and *response bias*, an index of the human's decision making criterion (tendency to say "yes" or "no"). When sensitivity is high, the probability of HITS and CORRECT REJECTIONS will be high and the probability of MISSES and FALSE ALARMS will be low. Response bias is a function of the relative values or costs of each outcome and the expectancy or likelihood of a signal being present. For instance, in a high-density traffic pattern, the probability of detecting other aircraft (HIT) will be high but the probability of a FALSE ALARM will also be high; MISSES and CORRECT REJECTIONS will be low. These outcomes are dictated by both the high *expectancy* of traffic and the high *cost* of a miss.

Information Selection

It is well known that information selection (sampling) in the cockpit is a function of both experience and processing strategies. Research has examined how pilots decide to attend to a particular display containing information to be processed. Review of this research suggest four conclusions:[2]

1. Sampling is guided by knowledge about the statistical properties of the environment
2. Human memory is imperfect and sampling is affected by the imperfection
3. Sampling improves when likely future events are previewed
4. High stress restricts the number of cues sampled

It has been found that a well-trained pilot will develop an optimal strategy based on the cost of failing to detect an event. These findings have significant implications for display layout guidelines. First, the most frequently sampled displays should be located centrally. Second, sequentially sampled displays should be located close together. Third, important displays should be the most salient, an extremely important guideline during times of high stress.

How much information can the human process in a single sample? When multiple relevant stimuli are present, how many can be processed at the same time? The answer to these questions involves the concept of *divided attention*. When both relevant and irrelevant stimuli are present simultaneously, can the human process only the relevant stimuli? Can the human avoid processing irrelevant stimuli? The answer to these questions involve the concept of *focused attention*. An important design guideline of spatial proximity emerges from these questions which determines whether visual stimuli are processed simultaneously (in parallel) or processed individually (in serial). Research has found that targets within 1° of visual angle of a focused target will be processed in parallel with the focused target.[3] Excessive stimuli within 1° of visual angle creates the undesirable effect of clutter, unless they can be differentiated by color or intensity.

A general display design guideline is that stimuli which should be processed simultaneously should be in close spatial proximity and stimuli that should be processed serially should be spatially distant. It has also been found that stimuli that are related on some meaningful dimension tend to be processed simultaneously. Object displays have been used to integrate stimuli both

2. Ibid.
3. Broadbent, D. E. (1982). Task Combination and Selective Intake of Information. Acta Psychologica, 50, 557-564.

spatially and in terms of meaning. Object displays combine multiple stimuli as attributes of a single object. For example, the artificial horizon provides orientation of a symbolic airplane with respect to the horizon to present both pitch and roll information.

Mental Model

The ability for a human to process information depends on one's knowledge state or mental model of a task. The model characterizes knowledge about the value or importance of various stimuli and about the statistical properties among stimuli. The mental model or knowledge base provides the context for determining the meaning of stimuli. It is well known, for example, that an experienced pilot has knowledge about the interrelations between events which occur on the various instruments in determining the state and state changes among aircraft systems. It is also well known that this knowledge base of experienced pilots forms the basis for efficient sampling of information, while for the novice pilot, this knowledge base is lacking and the mental model is poorly developed. One must remember that perception (pattern recognition) is a dynamic, cyclic process and underlies the dynamic nature of human information processing.

Memory

In human information processing theory, memory is composed of two components: working memory and long term memory. Working memory is the system that retains information for a short time until it is translated into action. Long-term memory is a system which stores information for later action.

Working Memory

The capacity of working memory is very limited. Research has found that the maximum number of unrelated items that can be retained in working memory when attention is devoted to rehearsal ranges between five and nine (7±2). Verbal information is typically retained in working memory using acoustic-phonetic rehearsal, while spatial information is typically maintained using a visual rehearsal code. Some recent research suggests that spatial information is less easily rehearsed than verbal information. If a list of information items larger than nine needs to be maintained in working memory, the items must be configured into related clusters or chunks. Failure to rehearse and interference from competing activities are the principle reasons that information is lost from working memory. Unless actively rehearsed, information in working memory will be lost within 10-20 seconds. Research has found that the following techniques may reduce working memory loss due to forgetting or interference: distribute information to be held in working memory over time; reduce the similarity between items; eliminate unnecessary redundancies; and minimize other concurrent perceptual or cognitive activities.

Long-Term Memory

Long-term memory traditionally has been divided into two classes: semantic and episodic. Semantic memory is memory of general meaningful information, such as how to follow a checklist of symbolic information presented by instruments, while episodic memory is knowledge about specific events which have occurred. The way that knowledge is organized in semantic memory is important in designing interfaces between humans and knowledge based information systems.

Decision Making

What is known about the strengths and limitation of decision making comes more from the extensive general psychological research rather than the very limited body of research on pilot decision making. This is true despite the fact that pilot error is listed as a primary or secondary cause in accidents for military and commercial aviation flight safety databases. Research indicates that the decision-making task has three general characteristics. First, the evaluation of multiple sources of information is involved in understanding the situation. This assessment forms the basis for responding. Second, the information which the pilot must assess is probabilistic and the expected costs and payoffs of a response are therefore uncertain. Finally, value and costs form the basis for most decisions but the payoff matrix is typically uncertain. A general model of human decision making which highlights the relevant information processing components is shown in Figure F-2.[4]

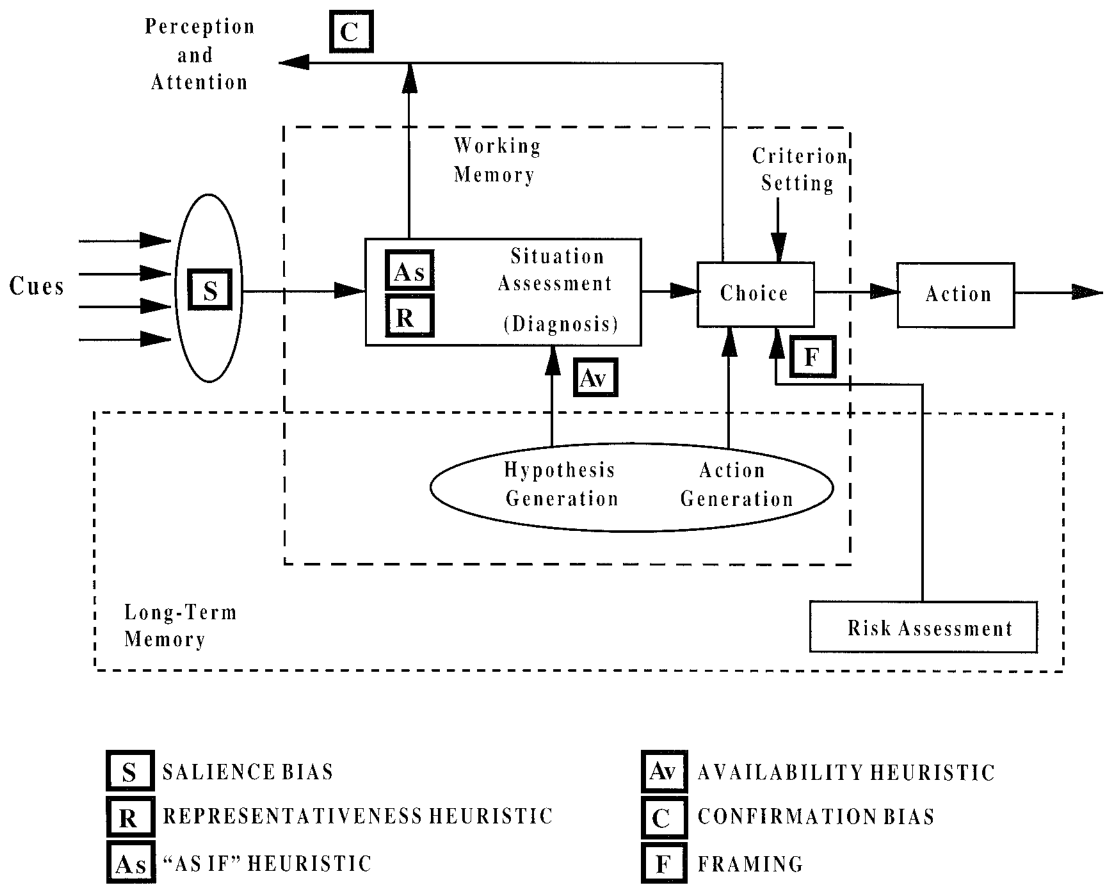

Figure F-2. Human Decision-Making Model

4. Wickens, C. D. & Flach, J. M. (1988). Information Processing. In E.L. Wiener & D.C. Nagel (Eds.), Human Factors in Aviation (pp.111-155). San Diego, CA: Academic Press.

Cues are sampled to obtain information for assessing (diagnosing) the situation. Cue sampling is based upon the mental model. These cues must be interpreted within a knowledge base contained in long-term memory to develop alternative hypotheses of the problem and to generate action alternatives. Biases, heuristics and the limited capacity of working memory influence the process. The critical choice point involves *risk assessment*, which is the evaluation of the probability of different outcomes and the assessment of the utilities of these outcomes.

Situation Assessment

In *situation assessment*, heuristics (mental rules of thumb) are used to reach a diagnosis of the current situation. These heuristics turn out to be shortcuts which may prevent the decision maker from obtaining the most accurate information but their use is justified because they are rapid. Research has found that decision makers do not necessarily process all of the information available to them from cues, particularly if they are under time stress. A pilot, for example, may focus on only a small number of available salient cues and ignore critical cues relevant to the problem. This is referred to as *salience bias*, indicated by S in Figure F-2. The *confirmation bias* (C in Figure F-2) is the tendency to seek cues which are likely to confirm an hypothesis that has already been tentatively chosen.

Hypothesis Development and Testing

The pattern of cues selected is matched in working memory with a mental model of *representativeness heuristic* recalled from long-term memory (R in Figure F-2). Since the mental model of the problem from long-term memory is very rarely identical to the problem in working memory, this heuristic may be limiting. Hypotheses developed and tested should include a reasonable number of possible hypotheses and should involve the most probable hypothesis. This involves the *availability heuristics* (Av in Figure F-2). The limitation of this heuristic is that the hypothesis considered may be the most available hypothesis in memory (i.e., the most recent experience or simplest hypothesis), but not the most probable. The a*s if heuristic* (As in Figure F-2) means that the decision maker treats all available information sources as if they are equally reliable. Yet differences in cue reliability remain an important factor in differentially weighting the diagnostic impact of different information.

Decision Development

Once the situation has been assessed, a *choice* of an appropriate *action* must be made. One of the options in this stage may be to seek more information - see the loop in Figure F-2 leading from choice to *perception* and *attention*. At this stage, it is important for the decision maker to choose an action with the most favorable expected outcome - that is the action with the highest expected payoff (utility). In decision theory research, this stage is typically represented by a decision matrix with different subjective probabilities and different courses of action. Typically, decision research has reduced the matrix to a 2x2 matrix, but in the real world the matrix may involve a larger number of possible actions and expected outcomes. If an optimum solution is to be reached, the risks (probability x utility) of different outcomes must be assessed. Research has indicated that humans are not skilled in assessing the probability of different outcomes and the risks associated with the outcomes. Indeed, expert decision makers often chose an action that in the past has resulted in favorable outcomes under similar situation assessments.

A general theory of choice decision developed by Tversky and Kahneman [5] involves the influence *framing* (F in Figure F-2). They have found that the choice between two actions, where one involves a risk and the other a sure thing, depends upon whether the problem is framed as a choice between gains or between losses. In many aviation decisions, the choice is between losses. Tversky and Kahneman found that humans are biased to choose the risky expected loss rather than the certain loss, even when the expected loss resulting from the risky choice is greater. For instance, a pilot may be faced with the choice of returning to his departure and missing a critical appointment (certain loss) due to a line of thunderstorms or continuing to his destination with the possibility of getting through safely and on time, but with a chance of getting to a thunderstorm and suffering a major disaster (risky expected loss). They have found that there is a decision bias toward the risky choice (i.e., going forward). If, however, the choice is framed between gains rather than losses, the less risky alternative is chosen (i.e., saving lives by turning back or keeping the appointment), the choice of turning back would be chosen.

Decision Quality

Training and experience have a significant role to play in the quality of human decision making. An expert pilot can quickly interpret patterns of environmental cues to reach a rapid and accurate assessment of a problem and has a greater store of hypotheses in long-term memory from which appropriate actions can be generated and tested to solve the problem. A greater repertoire of experiences can also be used to assess actions that in the past have worked in a given similar situation.

Selection of Action

Decision making in an aviation environment is sometimes time-critical. A large body of research has been generated concerning how humans respond to information under time stress. Unexpected events have been quantified in terms of the amount of information that they convey. According to information theory, the information H_i conveyed by an event i appearing in context X with a probability P_i/X is described by the equation:

$$H_i=\log_2[1/P_i/X]$$

The Hicks-Hyman law:

$$RT=a+bH_s,$$

states that given information conveyed by an event or a series of events, H_s, the time to respond to the stimulus events is a linear function of the information conveyed by the stimuli. It is well established that when a human is under time pressure to respond quickly, the chance of error increases. This phenomenon is known as the speed-accuracy trade-off. This trade-off is important in decision making in an aviation environment.

Multiple Task Performance

Many aviation situations impose concurrent and in some cases competing resource demands on the pilot. The attention resources required to simultaneously process these competing

5. Tversky. A. & Kahneman, D. (1981). The Framing of Decisions and the Psychology of Choice. Science, 211, 453-458.

demands have been shown to be highly correlated to workload. When certain pilot tasks are highly practiced, the performance of these tasks become "automated," that is, they demand little attention resources. Some models of attention predict when the human information processing structure of two tasks will be such that they interfere with each other (e.g., cockpit keyboard data entries interfering with manual flight control).

Figure F-1 indicated that attention resources can be distributed to different stages of human information processing, such as the pattern recognition, the decision and response selection stage and the response execution stage, as well as to working memory depending on task demands. Research has suggested that there are multiple human processing resources and that these can be distributed differentially depending on different task demands. A model of the multiple resources within the human information processing system is shown in Figure F-3.[6]

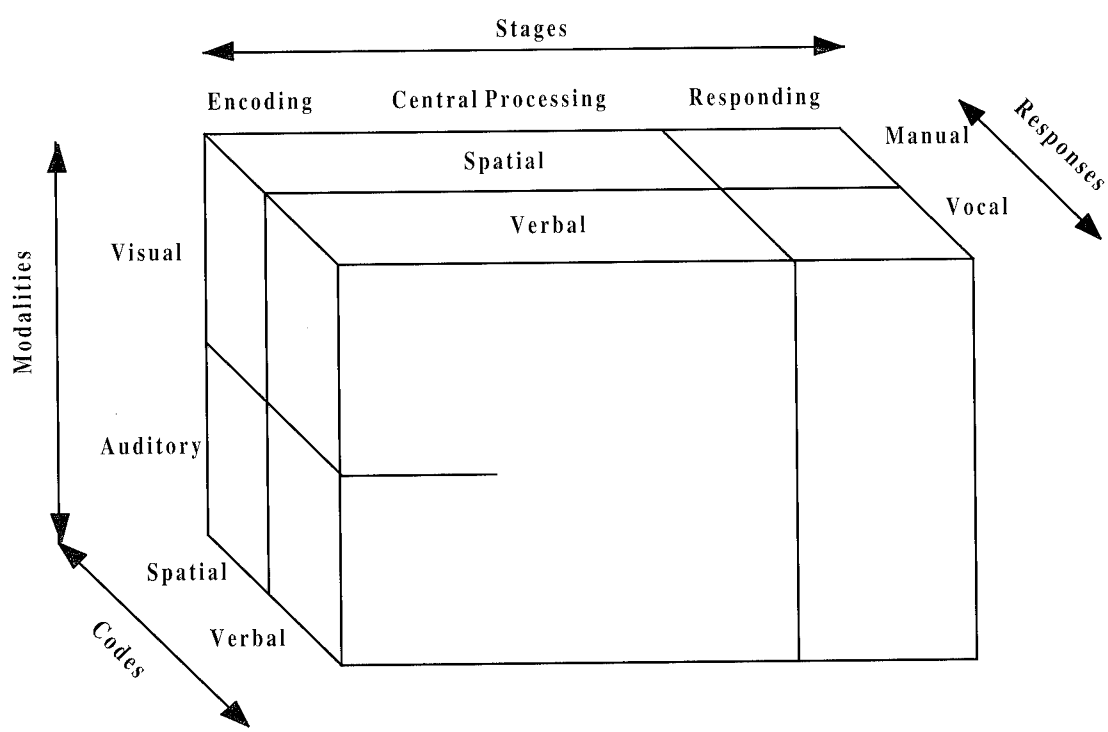

Figure F-3. Multiple Resource Theory

The model indicates that separate resources exist in three dichotomous dimensions, stages, modalities, and codes. The stages of perception and central processing (i.e., working memory) operations use different attention resources than response processes. Modalities of input include visual processing which uses different resources from auditory processing. The code dimension of human information processing indicates that processing spatial information uses different resources from those involved with processing verbal information. It is important to

6. Wickens C. D. (1984). Engineering Psychology and Human Performance (p. 302). Columbus, OH: Merrill.

note that the model does not predict that tasks using separate resources are perfectly time-shared, but that time-sharing efficiency is improved to the extent that two simultaneous processing tasks use different levels among the three dichotomous dimensions. The model can be used to guide the selection of the best interfaces in the visual-manual world typical of the combat pilot.

The Pilot's Task

While the problems of human information processing, decision making, and action are generic to all tasks involving human/system interaction, we will concentrate on the pilots' (aircrew members') tasks. Historically, the military pilot's task has been primarily a visual-spatial task. It has involved aircraft maneuvering and control, system management, communication, navigation, attack, and recovery. Military aviation is of necessity both complex and interactive. Since combat tasks involve an adversary, the military pilot's tasks are significantly more complex and interactive than the commercial pilot's tasks. This is particularly true for the fighter pilot's task, but to a lesser degree for the aircrew of the bomber, tanker and transport aircraft. The Air Force has a deep and abiding interest in improving the performance of piloted and unmanned aircraft in the combat environment. Future tactical aircraft will be operating in a much more demanding environment than they do today. The proliferation of advanced weapon technologies such as various forms of directed energy weapons, infrared electronic counter measures, new/upgraded conventional air to air, surface to air, and stand off weapon capability and the spread of these weapons across the spectrum of future adversaries will require critical, time-sensitive decisions to be made by our warfighters. This will place the tactical aircraft pilot in a more difficult mission environment than currently experienced.

Situation Awareness

One of the keys appears to be maintaining situation awareness. Situation awareness is the continuous examination of information about a system or environment, the combination of this information with previous information from working and long term memory to form an integrated mental model, and the use of that model in forming further perceptions, anticipating and responding to future events.[7,8] Wickens has proposed a model of the perceptual and cognitive processes involved in maintaining situation awareness and of the factors influencing those processes.[9] The Wickens model is shown in Figure F-4. (For an alternative model, see Endsley.[10])

Situation awareness is represented by the shaded area. The pilot obtains sensory input from the environment, primarily from displays, but also from out of the cockpit visual cues and voice communication, and uses available attention resources to form perceptions. The perceptual information is related to the information in *working memory*. The immediately retrievable parts of *long-term memory* are also considered to be available for situation awareness. *Prediction* indicates that the human has the ability to use information in association with a *mental*

7. Dominguez, C. (1994). Can SA be Defined? In M. Vidulich, C. Dominguez, E. Vogel, & G. McMillan (Eds.), Situation Awareness: Papers and Annotated Bibliography (Armstrong Laboratory Report No. AL/CF-TR-1994-0085) (pp. 5-15). Wright-Patterson Air Force Base, OH: Air Force Materiel Command.
8. Wickens, C. D. (1995, April). Situation Awareness: Impact of Automation and Display Technology. NATO AGARD Aerospace Medical Panel on Situation Awareness, Brussels, Belgium.
9. Ibid.
10. Endsley M. R. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. Human Factors, 37 (1), 32-64.

model to formulate an expectation of a future state. For prediction, the model is heavily dependent on resources in working memory. Situation awareness is influenced by several factors including *workload*, *effort*, *procedural knowledge*, and *action skills*. *Complexity* and *tools* influence the degree of situation awareness.

In commercial aviation, the flight management system (FMS) permits the pilot to program in advance various tasks for the system to carry out automatically during the course of the flight. Since the FMS carries out the tasks automatically, the pilot may lose the capability of maintaining an awareness of FMS actions, why the FMS is performing a task and what the FMS will do next. Sarter and Woods have systematically documented automation induced surprises which reflect a lack of situation awareness on the part of the flight crew.[11]

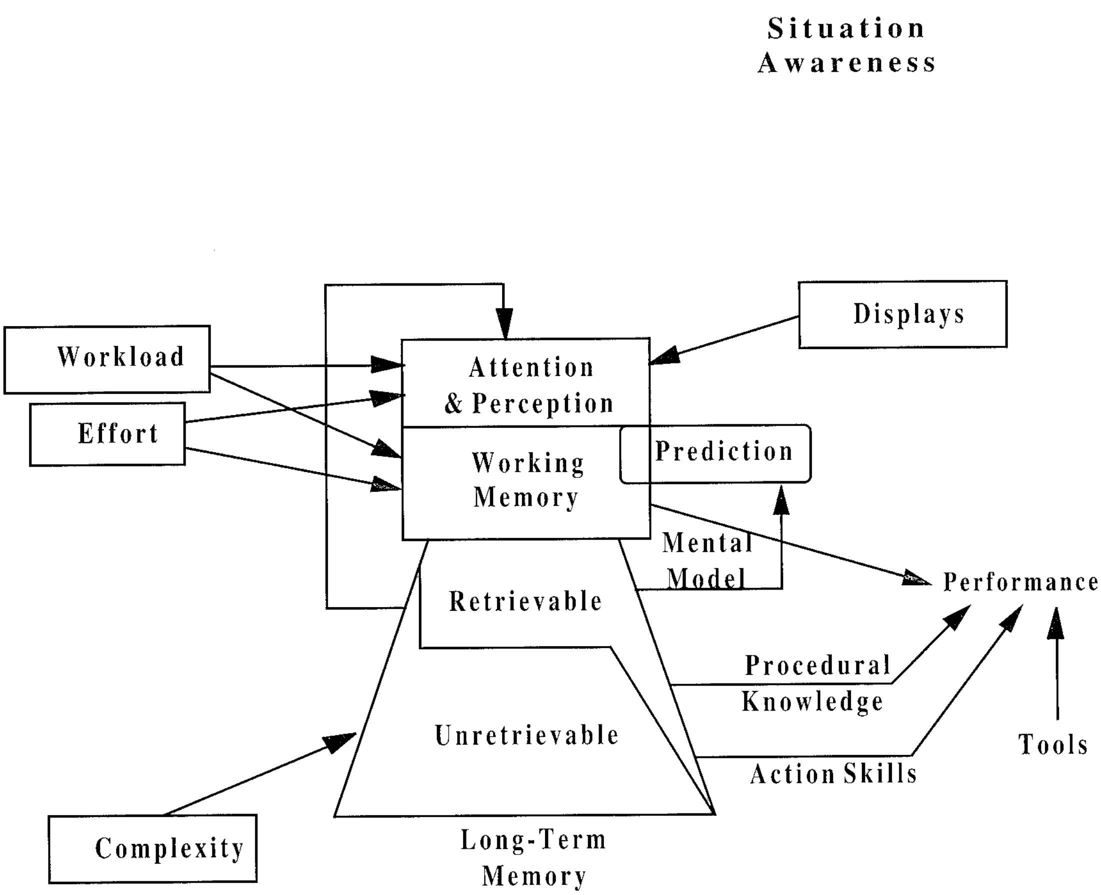

Figure F-4. Situation Awareness

11. Sarter, N. B. & Woods, D. D. (1995). How in the World Did We Ever Get into that Mode? Mode Error and Awareness in Supervisory Control. Human Factors, 37 (1), 5-19.

The automation of aircraft control tasks takes the pilot outside the control loop and relegates him/her to passive monitoring of control inputs and outputs. Research shows that the human is a very poor passive monitor of control processes. The result may be that the pilot's situation awareness of the status of automated modes and inner loop flight variables or parameters that will cause the FMS to initiate a control action will be significantly reduced. This has been termed "out of the loop unfamiliarity."[12]

Maintaining situation awareness becomes increasingly difficult as the complexity and dynamics of a combat military environment increases. In a combat environment, many decisions are required within a very narrow time span and performance is dependent on an organized, up-to-date analysis of the combat situation. Situation awareness will be a function of information system design in that the display must provide to the pilot the required information in a usable form without excessive processing. In the year 2020, information system designs need to be such that they present information in a way that is compatible with human information processing skills. Workload, stress, and situation complexity affect situation awareness.

Displays to Support Human Information Processing, Decision Making and Situation Awareness for 2020

Technology will exist in 2020 for displays which will support human information processing, human decision making and situation awareness to a much greater degree than at present. Cockpits will definitely become more automated and there will be automated decision aids for pilots involved in combat. In this environment, one concern is the problem of automation induced loss of situation awareness. There needs to be a focused effort to develop integrated temporal/spatial displays that will provide concise understanding of the current situation and salient alerting guidance for when future events will be expected.

The purpose of automation in the cockpit has been to remove the pilot from the control loop in order that the workload required to achieve mission effectiveness is not excessive or in many cases, simply to perform some function more effectively. As has been noted by some researchers, one result of automation has been to produce an out-of-the-loop unfamiliarity. Automation systems will be designed for 2020 which will require pilot intervention or approval of automation recommendations of control changes or attack options. As is the case today, the pilot may be the limiting factor if care is not given to following human factors principles in designing information displays and automation.

To date little research has been conducted which has evaluated display design formats to support automation-relevant situation awareness from a human information processing and decision making point of view. In the year 2020, these displays will be electronic and will provide dynamic updating capabilities. Advanced display concepts for global situation awareness should be evaluated using pilot performance in experimental studies which compare the advanced concepts against traditional concepts. It is important to know what human information processing mechanism is responsible for the benefit or for the cost of the advanced display concept.

12. Wickens, C. D. (1995, April). Situation Awareness: Impact of Automation and Display Technology. NATO AGARD Aerospace Medical Panel on Situation Awareness, Brussels, Belgium.

In organizing current research about displays for hazard awareness, Wickens has defined three critical features of display design: the scale of the display (breadth of coverage), the frame of reference, and the dimension of the display. Each of these features can be characterized as egocentric (pilot's viewpoint) or exocentric (God's eye view). Table F-1 provides a summary of these characteristics.[13]

Table F-1. Features of Display Design

	Egocentric	**Exocentric**
Scale of Display	Zoom In (Telephoto)	Zoom Out (Wide Angle)
Frame of Reference	Rotating (Track Up)	Fixed (North Up)
Dimension	2-D Planar (Top and Profile View)	3-D Perspective

Display Scale

For situation awareness, the scale should be determined by the distance from the aircraft for which information is needed. For greater distances, wide angle is needed; for near distances, a telephoto display is required. It is evident that wide angle displays produce a loss of spatial precision when the pilot is required to determine the location of objects.

Map Rotation

Electronic displays (maps) either present information in a track up or a north up orientation. The track up frame of reference rotates the electronic map in order to align the display with the heading of the aircraft. In the north up frame of reference, the orientation of the map is fixed to a north orientation. Extensive research has indicated that rotating maps provides the pilot better guidance for flight path control. When using a north up display, pilots are required to perform a mental rotation of the map when flying in other than a northerly direction. For situation awareness tasks that report ego-referenced knowledge (aircraft at 3 o'clock), rotating maps have generally proven to be superior to north up maps. For tasks which involve absolute coordinates (due east from current position), north up maps have been found to be superior. Wickens has advocated that a flexible frame of reference should be available for electronic maps.[14] If flexibility is incorporated, however, precise information of the format (menu hierarchy) that is in effect, must be available to the pilot (decision maker).

Dimension

For military tactical combat situations, Reising and Mazur have proposed that three-dimensional displays have an advantage in maintaining situation awareness.[15] Three-dimensional

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13. Ibid.
14 Ibid.
15. Reising, J. M. & Mazur, K. M. (1990). 3-D Displays for Cockpits: Where's the Payoff? Proceedings of the SPIE/SPSE Symposium on Electronic Image Science and Technology. Santa Clara, CA.

displays, however, present a fairly narrow forward field of view. Solutions to this deficiency such as wider field of view, removing the viewpoint of the display from the aircraft, and omnidirectional displays have limitations or provide some form of perceptual distortion. A second deficiency of three-dimensional displays is the problem with position estimation along the viewing vector of the display; since an infinite number of points in the 3-D space can be collapsed onto a 2-D surface, position estimation is ambiguous. This design limitation represents a potential loss of situation awareness when the pilot must know the position of objects in space.

The 2-D planar display that presents a top down and profile view of the airspace surrounding the aircraft has a number of advantages. The pilot can obtain unambiguous information regarding distances and angles separating the aircraft from other objects. Unlimited space on all sides of the aircraft can also be presented. A limitation to the 2-D display is that visual scanning is required to combine the top down and profile views, and cognitive effort is required to integrate the two views into a simple, integrated perception of the position of the aircraft and of hazards in the real world. Wickens has summarized the research as follows:[16]

1. Three-dimensional tunnel in the sky displays, in which the viewpoint corresponds to the position of the pilot, are superior for flight path control, but due to the narrow field of view are ineffective for situation awareness
2. Increasing the field of view of 3-D displays produces distortion which seriously disrupts situation awareness of external object location
3. 3-D exocentric displays disrupt situation awareness of the precise location of objects in the vertical and lateral axis, but do not hamper appreciation of the general layout of the topology
4. 3-D displays sometimes permit judgments to be made more rapidly than 2-D displays because of the time consuming visual scanning required with 2-D displays

Virtual Reality/Virtual Cockpits

In 2020, we will have developed virtual cockpits that will provide pilots with the situation awareness fundamental to winning the battle and the war. These cockpits of the future will allow performance in a "head-in-the-cockpit" mode where the threat from directed energy weapons dictates. It will be possible to provide the pilot with precise situation awareness by the use of off-board sensors under all weather conditions. This entails data fusion to provide the right information at the right time. Pilot workload will be relieved, providing an edge over an adversary that does not have the same capability. Additionally, information available to the pilot from off-board sensors would also be available to the command function.

The system will correlate and fuse sensor data in both space and time so that tracking of airborne and ground targets is performed seamlessly throughout the potential or real battle theater. Processing and transmission of sensor returns is performed rapidly enough for the strike aircraft to identify moving (time critical) targets. Off-board sensors, together with an on-board

16. Wickens, C. D. (1995, April). Situation Awareness: Impact of Automation and Display Technology. NATO AGARD Aerospace Medical Panel on Situation Awareness, Brussels, Belgium.

interrogator, are able to provide Identification Friend, Foe, Or Neutral capabilities to prevent targeting friendly aircraft and minimize collateral damage to non-target areas.

Development of virtual reality capability is the key. This will include immersive information concepts, new display approaches (panoramic to helmet mounted), and full use of human sensory capability. Development of modeling and simulation capabilities early on will permit a continuous focusing of research into those areas that will have the greatest payback.

Technology Needs

Technology which needs to be developed is focused on three areas: 1) ability to model the requisite areas of human capability, needs, and performance in a fashion adequate to determine hardware requirements, 2) ability to understand intuitive decision-making and how that relates to display needs/design/performance, and 3) continued development of virtual reality systems and how the human interacts with those systems.

As the designs of aircraft cockpits have become more complex, and as combat tasks have become more complex and interactive, designers have placed an increasing number of information processing demands on pilots and other aircrew members. More information is available directly in the cockpit. This information concerns aircraft system operation, navigation, weapon system information, electronic warfare systems, and information concerning detection and destruction of targets. Recent trends, however, have involved a higher degree of automation in military and commercial aircraft cockpits as a means of coping with pilot workload associated with task complexity and task interactivity. Advanced display technology has attempted to provide improved means of presenting information. In many situations, the task complexity and workload have been reduced by these efforts. In other situations, the pilot has been taken out of major parts of the control and decision making loop, thereby creating a situation awareness problem.[17]

17. In developing this appendix, the research of Dr. Chris Wickens has been heavily used. Dr. Wickens has written several excellent papers summarizing the current state of knowledge of human information processing, decision making, situation awareness and advanced displays from a human factors point of view as these concepts pertain to an aviation environment. Dr. Wickens also served as a participant on the Human Systems/Biotechnology Panel during the New World Vistas Study.

Appendix G

Cognitive Engineering

Introduction

Success in any endeavor has always depended heavily on the ability to obtain and use information. Some contend that future wars will be even more dependent on information than in the past. This is due to a number of factors including the lethality and mobility of weapons, the rapid pace of movement possible, the ability to operate in all weather and night conditions, and the world wide or global presence our responsibilities impose on us. Technology to gather and disseminate all types of data has been and continues to be a high priority in US defense budgets. This suggests that the amount of data available to future Air Force personnel will be greater than it is presently. But too much information can lead to poorer decisions by increasing the amount of data that needs to be integrated, thus adding clutter and confusing the decision maker.

Situation awareness refers to the ability of an individual to take in information, integrate it with previously obtained information and understand the significance of the result in terms of the task at hand. Considerable interest has been and is being exhibited in this concept because it may discriminate between effective and less effective pilots. Good pilots (and good decision makers) are probably able to perceive and integrate sensory inputs more effectively than others.

The study and application of knowledge concerning absorbing and making use of information in the form of decision making falls into the field of cognition. Cognition is a term that refers to all of the activities of the human that relate to the functions encompassed by the traditional term "mind," that is, thinking, knowing, remembering, problem solving, decision making, etc. It excludes such activities of the brain as sensory processes, emotions and motivation which, although obviously related, are not necessarily part of rational behavior. Perception is a term that relates to the interpretation of sensory inputs and has been shown to be somewhat dependent on learning so it may be included as part of cognition. Cognition is the characteristic that traditionally has been considered to separate humans from other organisms (although some scientists now consider the differences to be largely of degree rather than kind).

Design issues related to cognition have always been a part of Human Factors Engineering. Recently, spurred by the rapid advance of automation, and specifically, the role of the human and how we should design systems incorporating automated features, there has been an increased awareness of the importance of the cognitive area, spawning research in Cognitive Engineering. Similarly, research in the areas of selection, classification, and training has been emphasized to help ensure that decision makers at all levels are as qualified as possible.

The Future

Automation

Automation has been assumed by some to be a boon to system effectiveness. Experience accumulated to date indicates that in some situations this has been true. In others, however, the reliance on automation has resulted in serious system failures. The Three Mile Island nuclear accident is one instance in which an automatic system failure resulted in a multi-million dollar

loss which could have been much worse. Other highly publicized examples of failure of automated or semi-automated systems to correctly assess and/or communicate information that resulted in catastrophe include the *Vincennes* shooting down an Iranian airliner, the downing of two US helicopters by F-15s, and a midair collision at Pope AFB due to Air Traffic Control errors. Automation in modern 2-crew civil aircraft has been criticized because, although it reduces workload in cruise, it increases workload during critical flight phases such as landing and takeoff, and perhaps, in the case of unexpected events.

It is easy for system developers, operators and managers of fielded systems to be overconfident and/or complacent when the computer has been designed to accomplish a task or perform a function. Reliability goals are assumed to be satisfied by adding additional levels of redundancy. As computers increase in their capability, there is a tendency to design more and more automation into systems. Designers of commercial airplane cockpits have recently significantly increased the level of automation. Air Traffic Control systems are being designed to become largely independent of continuous direct involvement by controllers.

As experience accumulates, there seems to be increasing recognition that automation cannot be autonomous; the human must be retained to guide, manage, supervise, monitor and act as a redundant safety system. Toyota, for example, recently announced that it would continue to use human workers in its production of autos, and limit the further advance of automation into their auto production. Automation helps with the easy problems, not the difficult ones. With current systems this generally means that the human is placed into a role that largely involves monitoring the system. Unfortunately, it has been recognized for many years that the human is a relatively poor monitor. In addition, the developers of systems have generally assumed that automation will unburden the user if subtasks are performed by the system, thus reducing workload. However, often the workload has only been displaced and automation has imposed new, burdensome tasks onto the user. Therefore, the ability of the human to perform the role being assigned to him in many systems is suspect.

Examples of the problems in past and current automated systems are numerous. Clumsy automation includes the operating logic in the original Personal Computers (PC) which required the user to learn complex codes to interact with the computer. Developers overlooked the ability and willingness of users to learn codes that might take months of effort before sufficient learning had been acquired to perform meaningful work. Only when Apple came up with the menu approach, which reduced many memory requirements for learning code and also acted as a prompt for possible actions which allowed near immediate effective utilization of the PC by relative novices, did the PC become popular. After the introduction of menus, even technologically sophisticated engineers would wait in line to use an Apple rather than get immediate access to an IBM PC.

Another example of clumsy automation can be illustrated by problems arising in current generation commercial transport cockpits. Pilots can engage a number of modes to perform the same function. For example, there are least five different ways of changing altitude with current Flight Management Systems. The principle was to allow the pilot to pick the most appropriate mode for an existing set of circumstances. Some of these modes are relatively autonomous. For example, the altitude capture mode would maintain a given climb/descent until the assigned

altitude was reached, then transition and maintain the assigned altitude. Because the designers "rounded off" the maneuver to satisfy efficiency criteria, the maneuver was more abrupt than pilots would normally prefer due to comfort criteria. As a result, pilots would use a thumb wheel on the glare shield which directly controlled vertical speed to slow the transition. Unfortunately, unbeknownst to most pilots, use of the thumb wheel canceled the capture mode and airliners were busting altitudes. This example illustrates several problems with automation:

1. It may (probably will) add to training requirements
2. The automation should act in accordance with human expectations
3. In all cases, the human needs to know what the automation is doing, why it is doing it, and what it will do next
4. Unless there is unlimited time and dollars for training, there is probably a limit to the number of modes the system should have and the interactions between modes, because crews will have to establish appropriate mental models for each mode

As automation becomes more complex, the problem of establishing and calling up the appropriate mental model becomes more difficult. In other words, as automation increases and the interrelations between systems become more complex and more autonomous the problems of assuring the human and computer are always on the same page will become more important and more complicated.

The Air Force, through the Defense Advanced Research Projects Agency, recently had a program called Pilot's Associate which had the goal of developing an automated co-pilot to deal with the high workload in current and future fighters. Most of the effort was devoted to developing hardware and software to allow computers to take over some of the burdens imposed in high workload phases of flight. The assumption was the pilot would be able to assign lower priority duties to the co-pilot. Unfortunately, the added workload imposed in a highly dynamic, time critical world of air-to air combat required to interact with the computer to assign or assume rapidly changing priorities and needs was overlooked. Although technology spin-offs undoubtedly resulted from the effort, much remained to be learned in terms of how to improve the pilot/computer interface problems when the program was halted.

Belatedly, there is a recognition of the need to address the optimum role and functions of the human in automated and semi-automated systems and the design requirements for the Human System Interface for such systems. Since many of the functions of the human in advanced systems involve mental activities, there is an increased requirement for addressing cognitive issues in system research and development. Even when allocation of functions between the human and other components of the system has been effectively accomplished, automation imposes new and critical requirements to insure that the responsible human is able to quickly assess the current status and make rapid but optimal decisions for coping with the situations that arise. If we are to design effective automated systems, we desperately need research to understand and/or identify design principles that facilitate user friendliness and overcome human interaction problems. The alternative is to design suboptimal systems and then either correct the problems after the fact or let the human cope with clumsy systems either through training or reduced effectiveness.

Displays

All of the concern for cognitive design effectiveness is not limited, however, to automated systems, as important and prevalent as they have become. As noted above, problem solving and decision making are a vital component of almost every task, and become more important as responsibility increases. Commanders have an even greater need for effective information display because the decisions they make have greater ramifications.

Information processing is often accomplished through means of a display of some kind, whether it be a phone call, discussion, piece of paper with a note on it, a form, or an advanced electronic display. The way the information is displayed can hinder or promote the accurate and effective processing of the information. A display is the primary means a system designer has of influencing the user's processing of the information and the resultant action whether it be a lesson learned, a problem solution or a decision. Less effective display formats increase the difficulty of the task and required training time, increase the time to perceive meaning of information to be deciphered, increase the probability the information will not be used optimally, and increase the probability of error. These problems are rendered even more serious in the event of any kind of stress, such as need for rapid response, fear, sleep loss, and fatigue.

For the current discussion, it is necessary to make a distinction between data and information. Data are the outside world; information is internal to the person. Data may be considered analogous to a sensory input and information to a perception. Only when the data are interpreted do they become information. It doesn't help to see that a thermometer is at 100°C unless it is understood that water boils at that temperature. What's more, this may not be important unless it is known that the system malfunctions at 100°C. If data are to be useful, they must be presented in such a way that their meaning and importance are readily understood by the person who is to use the data. A map with aircraft position formation on it, is more "intuitive" than a dial displaying VOR data. Intuitive display suggests the displayed information's meaning need not be learned. While this is rarely the case, it makes the point that the meaning and significance of the information displayed must be almost instantaneously appreciated in the context of the job with minimal difficulty.

Sensors have been developed to obtain data of types and amount never before available. Satellites continuously obtain data through electro-optical, radar, infrared and other sensors. Additional data are gathered from other sources including electronic and human intelligence agencies. These trends will probably continue. Every decision maker from the weapons director to the pilot to the commander has the potential for being inundated with data. Yet, the need to make quick, correct decisions is so critical that consideration is being given to providing Real Time In the Cockpit display of additional data to pilots who are already complaining of being overloaded.

All the trends suggest that the quantity of data available to Air Force personnel will increase as new sensor technology becomes available. To be effectively utilized, this data must be analyzed, digested, assimilated, integrated, disseminated and displayed in a way that the human decision makers can understand and act upon the information in a rapid and effective manner. No matter how good, accurate, relevant, or timely the data is, it is of little use unless the

human decision maker is able to use the information to make the correct action. As technology advances and the world grows more complex, with the likely requirement for coordination with other, perhaps non-US forces, the world of the future is exacerbating the information problem.

The need for improved communication has been recognized by Air Force leadership. The recent Scientific Advisory Board Summer Study concerning "Information Architecture" highlighted a number of hardware deficiencies, and steps are being taken to assure an architecture and infrastructure that will enable data to be available to everyone who has a need for it. Complete compatibility should be implemented long before 2020. But attention in current efforts is primarily being given to the collection and dissemination of the data.

With respect to the Human System Interface, some effort is being dedicated to display technology, notably in the area of Virtual Reality(VR). Significant progress in this and other electro-optical systems such as large, flat screen, color CRTs, and helmet mounted displays offer distinct potential advantages and their development is being actively pursued by the Air Force. What is not being addressed in any significant way is the fundamental principles of how to make displayed information "intuitively" understandable to the user. Because we have better display media does not guarantee any better information processing. Content and format are more important than media. Shakespeare on cheap paper is better than a hack on premium quality paper.

Understanding cognitive processes for all human system design applications including developing effective formats is not an easy problem. The human brain has been called the most complex structure in the universe, containing about 100 billion neurons. As one noted scientist recently commented, "the simplest thing the brain does is sleep, but we haven't been able to figure [sleep] out yet."[1] Past studies of human information processing are analogous to trying to improve the performance of a black box without being able to open it up, but by studying input and output functions. The traditional approach has been to generate several different display concepts for a given task, and then evaluate them in some manner to determine which approach was best. Much of this work has been performed by developers trying to solve a given design need and principles were often not sought or disseminated widely even when defined. Often, no systematic evaluation was performed and the designer's concept was implemented assuming that humans are so adaptable they would be able to use the display even if some shortcomings were present. Human factors specialists did better than the typical cognizant designer because they added an understanding of the sensory-perceptual processes, usually including some form of information requirements analysis, and evaluated the display alternatives as objectively as possible. But often, display requirements were attacked in a piecemeal fashion; it was left to the human to integrate data displayed on different devices. The result has been less than optimal performance evidenced by added training costs, inefficiency, errors and accidents. Trying to produce effective integrated displays complicates the problem, perhaps geometrically.

Relatively recently, several developments have combined to make possible a vastly improved understanding of how people process information and, therefore, how to design information and control systems, and select, classify and train people more effectively to comprehend and apply information. These developments include:

1. Henriksen, S. J., as reported by C. Koenenn (1995, June 22). The Los Angeles Times, p. E9.

- Development and application of new methods of observing brain activity by neurologists, such as improved methods of monitoring the electrical activity of the brain
- Improved understanding of brain biochemistry and neurology
- Renewed interest in cognitive activities by psychologists
- The development of computer models, such as neural nets, of learning and perception by computer scientists
- The growth of interdisciplinary collaborative efforts including linguists and philosophers
- Effort at developing improved decision aids and artificial intelligence programs

Many of the people performing brain research do not have strong ties to defense efforts. Their work has been sparked by academic interests and the potential for dealing with mental problems such as those resulting from brain injuries and/or illnesses such as epilepsy or Alzheimer's disease. Although much of the current work still is limited to mapping areas of the brain and identifying active processes, insights and techniques developed from such research may provide a basis for a much improved understanding of how the brain performs cognitive functions and new, objective and sensitive indices for assessing techniques aimed at improving human mental performance. It is important that the Air Force promote programs that will take advantage of the emerging technology to assure its personnel are provided the necessary information and decision aids in a way that facilitates accurate and timely decisions and actions.

The Air Force should, however, focus on research in how to design intuitive displays and identifying information requirements for all information intense tasks, as well as identifying information requirements and operating logic to facilitate human-computer interactions. Much of the current sponsored research is aimed at improving display media such as VR and Helmet Mounted Displays. While these efforts are important and will facilitate sensory and timesharing needs, they do not address the fundamental problems of information overload or how to design compatible human computer interfaces or operating logic.

Decision Aids

It is known that humans do not always make optimum decisions. Sometimes all of the relevant variables have not been considered. There tends to be a response bias toward the first or last information considered. Sometimes all of the criteria are not prioritized adequately. Decision aids have been developed in the past to help medical doctors diagnose patients' ailments. These can be in the form of logic trees to guide the doctor's diagnosis, to suggest tests that might be applied, or even to suggest a diagnosis based upon inputs from the doctor. Many such decision aids can take the form of computer assisted decisions. These decision aids can be very useful in assuring the user has considered all of the relevant information and speeding up the decision. Mathematical models can be incorporated for some strictly analytical or deductive phases of the decision processes. Research into the needs, value and principles of design of such aids should be performed. The payoff would be better decisions arrived at faster.

Controls

Although this paper emphasizes human information processing and cognitive processes primarily as they relate to decision-making, some mention should be made of the relevance of cognition to the action taken.

Action following a decision is usually implemented in current and probably future systems by a control device of some kind (excluding brain activated control which probably will not be implemented by 2020, if ever, except for medical purposes such as assisting paraplegics). Much progress is being made in developing new technologies to increase the number of design options in implementing decisions. Many of these systems are based on the insertion of a computer to process information. "Look and shoot" systems are being developed. Speech recognition systems will be available which will allow both voice activated control with greatly expanded vocabularies and word context to be used to add meaning, reduce errors, and eliminate or greatly reduce the need to learn specific codes. Most, if not all, of the current limitations of voice actuation, such as the need for training the system to the speech characteristics of a specific speaker will be overcome. Use of noise cancellation techniques will facilitate the use of such systems in a noisy environment.

Touch panels integrated (overlaid) on computer displays offer great potential for integrating displays and controls and in conjunction with computers, reducing workload and improving situation awareness. One application that has been developed, for example, consists of overlaying a transparent touch panel on an electronic map. The operator simply points where they want to go; the system recognizes the x,y coordinates of the finger touch; the computer determines the most direct way of going there (or feasible options as constrained by air traffic control) from present position, and reprograms the navigation systems. Whole flight plans or changes could be quickly and unambiguously inserted, in both horizontal and vertical planes. Many other potential applications can be readily suggested, such as in command and control of forces, target description, and others.

Most of these devices will have specific applications. But their use must be carefully thought out in context of the total task and tested in representative scenarios. The concern can be illustrated by verbal displays which have been around for some time. Verbal displays (to "unburden" the visual channel) have value but also limitations. Verbal displays offer the advantage of not requiring a specific head or eye orientation to be perceived. In a quiet channel, they can quickly get attention. They also have the limitation of intruding on other tasks, or the information being lost in memory if that memory is not acted on immediately. In addition, the voice channel is already overloaded in many situations. They probably should be supplemented by visual displays to assure the human's awareness of the information is not lost because of short-term priorities in non-related areas.

To sum up, advanced computer technology when integrated with display technology will increase developers' options for allowing the human to interact with the system and offer great potential for facilitating human information processing in decision-making. Currently, few guidelines exist for assuring the potential gains will be realized. Inappropriate use will increase the difficulty of human system interfaces. Effective application requires a greatly improved understanding of human cognitive processes. This understanding has lagged behind computer technology and the result has been unnecessary workload and ineffectiveness.

Importance to the Air Force

For the foreseeable future, most if not all, critical decisions will be made by humans. Success at all levels is largely a function of the quality and timeliness of decisions. Therefore, successful execution of future Air Force missions will be a direct result of the ability of Air Force personnel to quickly comprehend the meaning and significance of the data presented to them and to make the appropriate decision from that data.

A current example may illustrate the difficulty some personnel have in using information displayed to them. At a briefing at Space Command Headquarters, it was stated that a satellite system controller sat at a console that included up to three CRTs and five telephones. The CRTs displayed as many as 1000 different symbols, some of which changed meanings as a function of the display. As a result, it took many months of on-the-job training to get personnel qualified and there was a significant error potential, particularly under stress. It is obvious that little attention had been given to the Human-System Interface during the development of this system.

One of the human's significant values is the ability to cope with unanticipated circumstances. In order to cope, however, the human must be able to comprehend the situation to be handled. Any lack of understanding will adversely affect the decision made. The pace of current and future warfare will probably continue to increase. The amount of data available to leaders to assist in making decisions will also increase dramatically. It is vitally important that methods be developed to enable decision makers to cope with the full comprehension of the data as quickly and intuitively as possible. A little effort has been devoted to this but almost always specifically aimed at aircrew. Almost all Air Force personnel are involved with taking up and using information.

Vision

By 2025, effective intuitive display formats will have been developed for all positions requiring the human to rely on artificially displayed information. Human-computer interactions will be facilitated by operating logic, displays and controls that assure the operator or commander has all the information needed to address almost instantly all contingencies. Decisions aids will be incorporated appropriately. Assessment of the situation and selection of the most effective response will be greatly facilitated. As a result, forces are deployed and actions taken to thwart enemy intentions and attack weaknesses in the most effective manner. Lives are saved and material and other costs are greatly reduced. The overall force required to meet mission requirements will be reduced, as will training time.

Key Technologies

The key technologies for research directed at developing an understanding and guidelines for effective display of large quantities of information to facilitate decision making include:

- Cognitive Psychology
- Brain Neurology and Biochemistry
- Computer Science and Modeling

It is believed that collaborative, interdisciplinary studies will be especially valuable. Among the applied sciences and technology opportunities for applying the results of research to achieve the goal of improved decision making are:

- Improved selection and classification of decision makers[2]
- Improved training
- Improved displays for all sorts of human activities
- Development of effective decision aiding methods
- Improved methods of applying and controlling automated systems

The primary near term need is to initiate efforts at understanding information requirements of Air Force decision makers, and identifying methods of integrating and fusing the information into representative formats for evaluation by traditional empirical methods. Basic research should be funded to determine principles of how to make displayed information "intuitive" and how to control or implement such information. It is likely that most jobs will require information and integration unique to that function. Therefore, research should be devoted to determining what "to be available" information is desired/required for the specific jobs to be performed. Perhaps the initial focus should be on aircrews, since the time stress for their functions is apt to be greatest and there is a tradition of display innovation in the aviation industry. But attention should also be devoted to determining the information requirements of commanders at all levels since their decisions will have the greatest significance. Other operators and maintainers needs should also be addressed. Brain researchers from various fields should be exposed to the problems and may serve as consultants initially to pique their interest and increase their understanding and awareness of potential applications of their work. The Air Force should initiate an activity to monitor and assess the brain research technology to determine when it is appropriate to start using the developing techniques and research findings to improve the display and integration of the required information. Perhaps most important, the Air Force should establish human performance requirements. Contracts should require specific requirements be met with as much emphasis as other system requirements.

Hurdles

The primary initial hurdle will be the inertia in the Air Force and the limited recognition of the need for much improved human system interfaces. A second hurdle is the gaining of the confidence of Air Force command that truly significant performance improvements can be achieved through attention to improved human system interfaces for information processes and for decision-making.

The research hurdles are there. We may never fully understand how the brain functions. Current research is promising but even the most optimistic acknowledge that only the most limited questions are being addressed. It is not necessary to fully understand the brain, however, to develop useful tools that can identify how we can facilitate human performance.

2. See also paper on selection and classification in Appendix H.

Benefits

It is nearly impossible to estimate the total impact of maximizing the quality of human decision making. One decision could make the difference between success and failure of a major campaign. Even some relatively minor decisions could save millions of dollars, and/or save many lives and much equipment. The ability to understand the significance of incoming data and deploy forces effectively against a missile threat could save many lives and major property damage. If the study and application of knowledge in the area of cognitive science resulted in an improvement of only 10% in the quality and/or timeliness of decisions, the potential benefits would be enormous. Training time for many jobs would also be reduced. The benefits of the investments in C^4I technology will be significantly diminished unless attention is dedicated to discovering the most effective way of displaying the collected data and facilitating the decision process.[3]

3. Regian, J. W., Day, E. A., and Shebilske, W. (1995). Experts in Battle: Selection Training and Human-Systems Design. Unpublished paper prepared for the SAB Human Systems/Biotechnology panel on New World Vistas. Regian, Day and Shibilske have written an excellent paper noting the potential gains resulting from a revamping of the methods and emphasis of the Air Force in selection, training and human-system interface design without resorting to significant advances in science or technology.

Appendix H

Personnel Selection and Classification

Introduction

The US Military has used Selection and Classification testing since World War I. Selection tests are aimed at determining if the person should be employed; classification tests at determining the job category for which the person shows the greatest potential for success. The Air Force developed and applied an extensive and very successful program for aircrew selection during World War II. These tests included both psychomotor and mental aptitude testing and were credited with saving several hundred million dollars through reductions in wash-out rate in the pilot training programs. Savings from lowering the washout rate resulted from saving instructional time and resources that otherwise would have been wasted (in 1942 dollars, a P-51 cost about $50,000). It is highly likely that not only time was saved, but that the end products, i.e., pilots, navigators and bombardiers, etc., were also of higher quality.

Selection testing employed by the Office of Strategic Services included many non-cognitive factors such as personality and interest variables in addition to measuring cognitive abilities. Instructor assessments during training of these non-cognitive factors were systematically incorporated. This program had a very high success rate and has been considered one of the most successful programs ever devised. Although it was relatively expensive, the criticality of the jobs justified the cost.

The tests used today are direct descendants of the original Alpha and Beta tests used by the army in World War I.[1] Since 1980, Air Force enlisted personnel have been selected using the Armed Services Vocational Aptitude Battery. These tests are largely paper and pencil multiple choice tests which measure cognitive abilities. They have been validated as predicting technical school success. Validation test scores of schoolhouse success generally yield correlation coefficients of around .30-.40. This is considered fairly good for today's measures, but it leaves much room for improvement since a correlation of this magnitude accounts for less than 16% of the variance in criterion performance. Because of the large numbers of recruits involved, a high correlation is not required for truly significant savings. A correlation of similar magnitude exists for pilot training selection measures. Here, however, significant cost savings result not from the large numbers of trainers, but from the high cost per trainee.

In many jobs requiring relatively low performance, there is a tradeoff between the cost of testing and the payoff. Higher skill and performance requirements justify higher test costs. There is also a tradeoff in the selection ratio; that is, the ratio of the number of applicants and the number of positions to be filled. If this ratio is unity (everyone applying will be hired), selection tests are of little value. Classification tests to place people where they will perform best for jobs that require the person to have superior characteristics are still valuable. Obviously, computers will allow faster and cheaper data processing. In addition, current paper and pencil tests can be presented at a display console, be self-administered, reduce cheating, and minimize other administrative problems.

1. Sawin, L. I. (1995). Selection and Classification-A Holistic Approach. Unpublished paper.

Current test programs are limited insofar as they rely primarily on assessment of cognitive abilities. Great improvement is potentially possible since many authorities are convinced that there are many more aptitudes than the eight or so the tests claim to measure. Guilford, for example, hypothesized as many as 120 different mental abilities in his "Structure of the Intellect" Theory and developed "factor pure" tests for many of these (See Figure H-1).

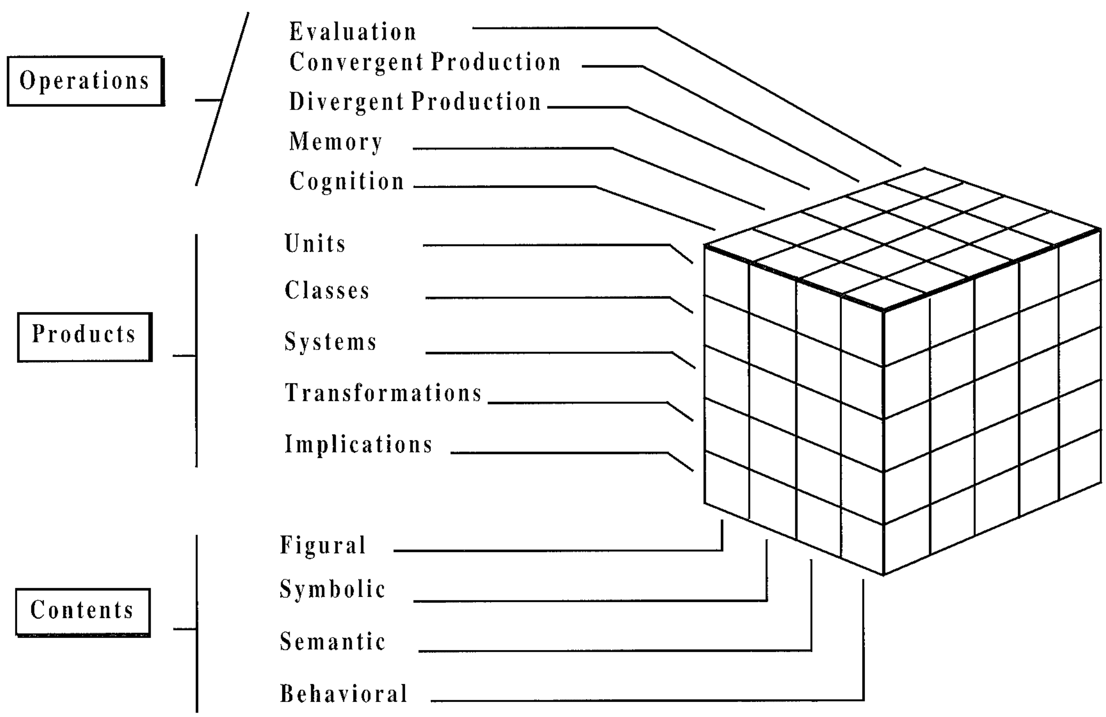

Figure H-1. The Structure of Intellect[2]

Interest, motivation, and personality factors are also believed to have a significant bearing on job success, and although, in the past, measures of interest and personality factors were included in some selection and classification batteries, they have been dropped from many for a variety of reasons. The validation method typically used is correlation of test scores with success in training. While important, success in training is not the ultimate criterion of concern. Real job performance should also be used as the criterion, though it seldom is. It is highly probable that many of the factors in job success are only partly correlated, if at all, with school success.

In addition, missions and jobs are changing. Technological developments such as automation, computerization, and various job aids are changing job requirements. Demographics involve another set of factors which may influence a test battery's validity, and it is almost certain that the Air Force in the future will draw upon a population of recruits different from today's.

2. Adapted from Guilford, J. P. (1967). The Nature of Human Intelligence. New York: McGraw-Hill.

The Air Force, through the research activities of the Armstrong Laboratory (AL), has recognized the need for improvements in selection and classification methods. At the present time, a long term project, the Learning Abilities Measurement Program, is being conducted with the collaboration of AL and the Air Training and Education Command (AETC). This research, however, is still limited in that its focus remains on cognitive and psychomotor abilities.

Most of the work in developing test batteries has been quite pragmatic. Little theory development has been involved, although there has been a long standing controversy over whether intelligence is made up at least partially of a "g" or general intelligence component in addition to specific aptitudes. A hallmark of the AL efforts is that it includes an attempt to do theory testing and development, and this research is definitely needed.

The Future

The role of the US military has changed from protecting against the primary threat of the Soviet Union to that of promoting world peace around the world by suppressing aggression, supporting humanitarian activities and, perhaps, increasing its role in anti-drug activities. With the downsizing of forces and increased complexity and variety of threats there will be a requirement for greatly increased flexibility of our forces. Personnel must be ready to react quickly to threats anywhere in the world. These factors will make it necessary for US personnel to become competent in a variety of different roles. F-15E crews already have more than 30 different missions types to perform. Relatively small, multinational teams will probably be formed to respond to the threats. Selection and classification methods must reflect these factors if training and performance requirements are to be satisfied with minimal cost and required effectiveness. Fortunately, some new developments in a variety of different arenas offer potential for greatly improving our understanding and measuring of human capabilities.

Among these developments are the increasing understanding and improved measuring techniques in brain functions. These may allow more objective techniques to be used to identify promising people early on and throughout the selection process. Work to date in this area has indicated that there are differences in the way males and females process information.[3] It has also been found that older people change their mode of processing information.[4] Research performed in the next 20 years will certainly identify many new relationships between how individuals process information, react to emotional stimuli, and performance in specific functions. The brain is the center not only of the mind, but also of emotions, motivation and most other things that make us individuals. These discoveries will offer the potential of providing new, non-cheatable methods of selection and classification. Research on brain function offers an exciting new vista in the areas of selection and classification as it does in other areas.

One of the reasons the psychomotor tests were dropped from earlier Air Force selection testing was the unreliability of the equipment used to administer the tests. The "Four Limb Tracking Test," for example, required an electromechanical device to determine the applicant's eye-limb coordination. This equipment often failed and either the applicant had to be rescheduled or the test score was lost. The added expense of maintenance and repair contributed to the problem. Current computer technology can overcome these limitations as well as provide new

3. Kimura, D. (1992, September). Sex differences in the brain, Scientific American, 267 (3) 118-125.
4. Selkoe, D. J. (1992, September). Aging brain, aging mind. Scientific American, 267 (3) 134-142.

opportunities to test newly discovered attributes related to job performance success. The Israeli Air Force, for example, is employing a computer game to measure time sharing ability, an important ingredient of situation awareness, in their pilot selection process and training with considerable success.

It should be noted that selection data (test scores, education level, etc.) are seldom used in a formal way beyond the initial selection and classification decisions that admit (or exclude) individuals to certain training programs and/or career fields. With the substantial increases in data storage and computational capabilities now available, it would be possible to add a wide variety of data and measures that will accrue during the course of the individual's training and operational job assignment experiences. Steps have already been taken to computerize virtually all data that accrue in the individual's service file. The use of such added "Air Force Life History Data" to the predictor data pool should allow, assuming conduct of the necessary supporting research, much improved accuracy in subsequent job and mission performance prediction. This, in turn, would allow a much more precisely focused management of Air Force personnel resources, i.e., putting the "right person in the right job." This would produce both cost savings and enhanced mission performance.

Conceptually, the above procedure would involve extending the selection/classification system over the entire career of the individual rather than limiting it to just the initial application as the individual enters service and/or training in a career field. It would entail the development of a number of selection screens that would be applied over time as the individual progresses through their Air Force service. At each screening point, available predictor data would involve the data set from the previous screening point plus data that would accrue between the previous screen and the subsequent one. Correlational studies would be required to determine which items in the data pool would be effective in predicting the next levels of criterion performances. As was previously noted, for example, the factors that predict success in training may differ from those that predict job performance success. The procedure described here would recognize such differences empirically and should increase the precision of prediction of both training and job outcomes. There is a question as to how far into the person's Air Force career or service such a predictor enhancement would be useful and cost effective. Perhaps it would see maximum utility only for the first five to seven years of service.

A rough depiction of the selection /classification process described is given in Figure H-2.

The initial selection/classification decisions are based on the data set shown as screen 1 (S_1). As depicted, this data set consists of a variety of cognitive measures (C_1, C_2, etc.), non-cognitive measures (N_1, N_2, etc.), life history data (L_1, L_2, etc.), and physical measures and history data (P_1, P_2, etc.). Differences empirically derived, which should increase correlation ($R_{S1\text{-}TD1}$, etc.), predictions and selection/classification decisions are made relative to training regimen (T_1, T_2, etc.) and subsequent job and mission assignments (JP_1, JP_2, M_1, M_2, etc.). After these initial selection/classification decisions are made, additional data (TD_1, TD_2, etc.) are added to the predictor data pool to allow derivation of predictor equations at the S_2 level ($R_{S2\text{-}JP1}$, $R_{S2\text{-}M1}$, etc.). In similar fashion, subsequent screens and predictors are developed for subsequent career stages and selection/classifications decisions. In this way, sharpening of the predictor equations should occur at each screen level.

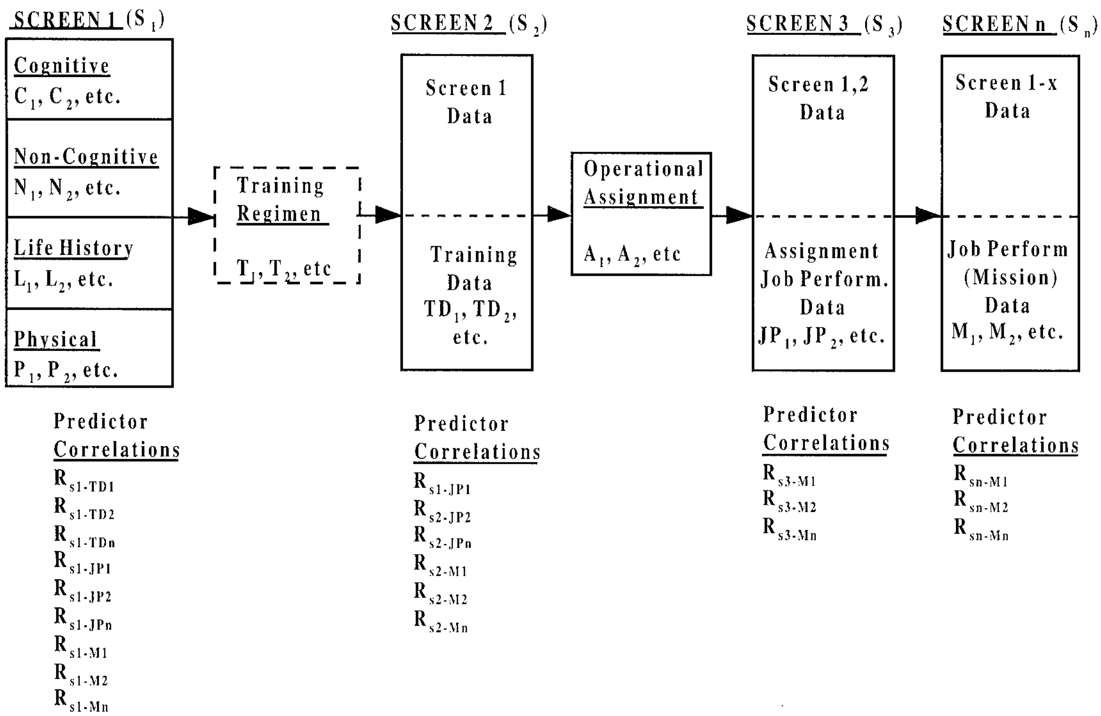

Figure H-2. Initial and Secondary Selection and Classification Process

Even now, some authorities in the field are looking for ways of using job performance rather than schoolhouse performance as the validation criterion for selection methods. Currently, work also is being done to improve our test methods by addressing non-cognitive abilities and by renewing the emphasis on incorporating psychological theory in the development of selection and classification. Flexibility, ability to work as a team player, dedication, willingness to "go all the way," ability to handle stress of various types, and other characteristics are undoubtedly as, or more, important to job success than academic performance. Adding these dimensions to the selection and classification process will offer the opportunity to substantially increase validity coefficients. The ability to measure these characteristics early and throughout one's career will greatly improve all facets of the human resources process, including training methods, and can result in significant cost savings and increased levels of job performance.

Importance to the Air Force

The Air Force currently inducts more than 30,000 new recruits every year. The cost of training these recruits is enormous. It costs well over a million dollars for the training of a single pilot. Advanced technology will simplify some tasks but complicate others. Two-level maintenance has already made it necessary for flightline personnel to become more flexible and has added to training requirements. Improved efficiency in the selection and classification process will not only substantially reduce these costs, it will also result in a much more effective force.

Key Technologies

There are a number of key technologies that must be advanced if the promise of improved selection and classification is to be realized. Some of these are relatively mundane; others are quite esoteric. They include:

- Research into the biochemical and electrical activity of the brain, as well as other physiological and psychological indices as they relate to human performance
- Development of valid, reliable, and easily measurable job performance measures
- Development of easily used and inexpensive techniques of measuring brain function at the physiological level
- The development of new selection and classification methods to include more extensive multiple regression predictor models, not specifically related to physiological brain activity, but including both psychometric and physiological measures
- The performance of selection and classification studies into areas in addition to cognitive function, incorporating actual job performance as the criterion

Fortunately, much of the physiological research into brain and other activity will be performed without substantial Air Force support by academicians and those in the medical profession due to its relevance to correcting problems resulting from injury or disease.

The Air Force has in place a qualified team of researchers for the development of the non-physiological measures, including well respected cognitive psychologists. It also has an unsurpassed opportunity for performing selection and classification studies with recruits due to the existing relationship between AL and AETC.

Hurdles

Aside from the performance of the research in brain and other physiological methods and relating this to performance, the primary hurdles include developing physiological and non-physiological measures that can be quickly, easily and inexpensively used with large groups of inductees or in follow-on classification. It is believed that with the advancement of electrode and other sensor capability that will almost certainly occur in the next 20 years, this problem will be solvable with reference to physiological measures. Computer processing of physiologic data will be possible and relieve much of the tedium and expense of analyzing data. Most of the other requirements are capable of being performed today if adequate attention and resources are allocated, particularly in the non-brain related testing areas.

Will the Hurdles be Overcome?

Yes, unless the priority is reduced and existing programs are eliminated and/or tracking of relevant brain and other physiological research is not accomplished.

Benefits to the Air Force

It is difficult to quantify the potential benefits because they will be influenced by a number of factors not under the control of the researchers, such as the size of the pool of inductees and

the number of inductees per unit time. The potential of improved selection/classification procedures for cost savings and improved job performance by personnel in all Air Force job categories is very large. The spin-off is huge for other services and the civilian population at large. The Air Force has a unique capability for performing the research and establishing the methodology for more effective personnel selection and classification systems.

Appendix I

Precision Guided Training

Introduction

This paper will attempt to sketch a view of what Air Force training may be some 25 years hence in the year 2020. As such, it will comment on both the training of pilots and other aircrew personnel as well as on the training of non-aircrew specialists, particularly maintenance personnel, and the command and control personnel who are responsible for force employment and management. While it is anticipated that these next 25 years will see some rather remarkable changes in such training, it is anticipated that training activities and methods, by and large, will not be radically different from those that presently exist and, indeed, which have existed for some years now.

It is clear that Air Force training will have to become much more effective and efficient in the 21st century. While Air Force training has done a creditable job in the past, having produced what is by far the most effective air fighting force in the world, it must be noted that it has done so, at least in part, through the sheer strength and volume of resources, material and financial, that it has been able to bring to bear on its training requirements. Increases in training effectiveness and efficiency that have been clearly attainable within existing technology have been degraded and retarded significantly because the surfeit of money and other resources that has been available to the Air Force training community has allowed us to be inefficient. Unfortunately, the favorable resource position that it has enjoyed since the beginning of World War II no longer exists, and the Air Force must attend closely to the affordability of its training. To do this, the Air Force must improve its training practices significantly if it is to fulfill its future role in the national defense during the 21st century. It could be argued, even, that the bleak fiscal outlook that now faces the Air Force will provide the "necessity" that has been missing and will lead to the "invention" and wider application of advanced training technology in the future.

As we look to the future of Air Force training, it is clear that we face a period of progressively more difficult budgetary constraints as well as a society and world in which the military must conform to many restrictions on its activities, environmental and otherwise, that it has been able to ignore in the past. The principal resource on which aircrew training has relied in the past, a relatively generous allocation of aircraft flying hours, will become in increasingly short supply because of fiscal constraints and reductions in the number of aircraft in the fleet. The progressive aging of the fleet will further impair flying hour programs. Complicating this situation likely will be a broadening of Air Force mission responsibilities in peace-keeping and humanitarian support activities which will compete with training for the available flying hours. In addition, numbers of personnel to support the all-important maintenance functions will continue to decline, even as the complexity of aircraft systems increases, with the result that maintainers will have to possess a wider array of skills than in the past. Under these circumstances, both training and personnel management practices will be especially critical to providing an effective maintenance capability.

Of course, these are not the only factors that will dictate the climate in which training will take place in the year 2020. The world political situation will be all important, as will

technological developments in aviation and related fields. The nature of the threat which we will face in 2020 will be different, irrespective of who our friends and foes might be at that time. The threat is becoming progressively more pervasive and deadly, and the technology advantages which the United States has enjoyed over the past 75 years are disappearing. Advanced technology is becoming increasingly affordable and increasingly available throughout the world. Even the most backward and poorly developed third-world countries will possess weapons with the capability to kill or seriously restrict many of our current and future weapon systems. The threat of chemical and biological weapons in this regard cannot be ignored. Obviously, progress will continue in the development of our defensive systems as well as in offensive systems, but we will not be able to treat the capabilities of our potential foes with disdain and non-concern. As has always been the case when technology and forces are at or near parity, superior training and leadership are the prime determiners of battle outcomes. This fact cannot be ignored in the year 2020.

We must note too that the nature of warfare is changing, and it is changing at a rate that we have not experienced before. Clearly, information processing and intelligence have increased in importance dramatically in modern warfare, a trend that will continue. The pace of modern warfare generally has outstripped the capabilities of the human operator to handle the information processing load. As a result, we see a constant increase in automation and use of the computer in weapons systems as a means of relieving the operator of aspects of his/her task loading. It is even possible, perhaps likely, that manned aircraft operations as we have known them, particularly air-to-air combat, may cease to be a major factor in future Air Force activity While it is clear that transport aircraft will continue to be manned, the air combat pilot of the future may be a teleoperator and only a virtual presence in the air, though not by the year 2020. Nevertheless, there will be unmanned vehicles in use by the Air Force in 2020 for certain missions. The training problems this will present are numerous and must be prepared for. The evolving technology of virtual reality will likely play an important role in such training. In addition, we must note that space looms as an ever more important aspect of the future battle environment for the Air Force, a factor that will also present new training demands. As a consequence of these and similar changes that loom in the future, the nature of weapon systems and the nature of the aircrews' jobs have changed in a number of fundamental ways. Training must keep pace with these changes.

Comparable changes are occurring also with respect to the jobs of maintainers and other Air Force specialties. The advent of composite and smart materials in the new aircraft (scant though the numbers of *new* aircraft will be), the increasing presence of computers and digital technology in aircraft and support systems, and the accelerating aging of the aircraft fleet all present new challenges to the maintainers, challenges that were of little or no concern until recent times. The move to two-level maintenance and the reduction in number of maintenance job specialties present still other challenges to the maintenance and logistics support systems. Training and personnel systems in 2020 must address these new demands also.

Another major dimension of change is the movement toward joint and coalition operations as the norm for Air Force combat activities. We have paid inadequate attention in our training to this operational change, in part perhaps because of lack of command emphasis, but also because of the costs involved and the lack of suitable training technology to support such training effectively. The same observations can be made with reference to our understanding

and training of information processing and decision making at high levels in the command and control structure. This situation must be addressed as the Air Force moves into the next century. Additional changes in operations, already occurring, that must be addressed include the increasing emphasis on special operations and the emergence of peace-keeping and humanitarian missions, not to mention anti-terrorism and drug-interdiction, as major Air Force operational requirements. These emphases must be reflected in future Air Force training and system design. Other major changes that must be addressed by future training systems include the requirement for rapid response on a world-wide basis, the 24-hour, day-night operational capability, and the likelihood that power and force projection will come increasingly from US bases rather than from overseas locations with pre-positioned forces and supplies. Finally, there is the possibility of major changes in roles and missions among the US military services.

The preceding discussion has sketched only in a superficial way some of the challenges that will face Air Force training in the year 2020. To meet those challenges will require significant human systems research effort and significant changes in our way of doing things. Fortunately, major progress has been made over the years in the various technologies that underlie our training and other human system capabilities, and progress will continue in these technologies over the next quarter century. The technologies that are relevant to future training were reviewed at length in the Scientific Advisory Board (SAB) Summer studies of 1992 and 1994. Consequently, they will not be visited in detail here. We believe those technologies will be sufficiently mature to meet the challenges of the 21st century and will allow training and manpower/personnel systems that are geared to meet future requirements in a cost effective manner.

Trainee Characteristics

Training systems must be designed with recognition of who the trainees will be, their backgrounds and experiences, their psychometric characteristics, and their motivations and goal structures. In 2020, the Air Force likely will continue to be an all-volunteer force, and it will be able (assuming proper incentives are available in terms of pay, career opportunities, and quality of service life) to attract a sufficient pool of high-quality trainees from the civilian world. These trainees are expected to be from the upper half of the intelligence/aptitude distributions, possess a sound secondary or college education, have competency in basic academic skill areas, be computer literate and have experience with many computer applications, and be well motivated to perform their service jobs, seeing those jobs as stepping stones to civilian careers if not as part of a long-term military career. However, it should be recognized that the demography of the recruit population is changing. The proportion of minorities in the recruit population is increasing and will continue to do so into the foreseeable future. While there may be many implications for training that stem from the demographic changes, the increase in numbers who come from non-English speaking ethnic backgrounds is a factor which may affect the effectiveness and efficiency with which training programs and materials impart to such personnel the information necessary to training and operations. In short, while the Air Force can expect the general quality of its trainees to show progressive increase between the present and the year 2020, thereby yielding a highly trainable and adaptable work force, there are many aspects of the changes in trainee populations in 2020 to which Air Force training systems will need to adjust.

In addition to the general changes in trainee quality, note should be taken of developments in the areas of personnel selection, classification, and placement technologies that are discussed elsewhere in this report. Selection and classification techniques in the past have seldom accounted for more than 20% of the variance in trainee performance in training and on the job. Techniques presently under development show promise of significantly increasing the effectiveness and efficiency of selection, classification, and job placement. This means that future trainees will be better fitted to the training regimens and jobs to which they are assigned, a fact that will make both training and operations more precise and more cost effective. Cost effectiveness in training has been an area of neglect in the past, but budget and force constraints will require that it receive greater attention in the future. The design of training systems, (i. e., the design of training equipment and training programs), is clearly the major factor in training cost effectiveness, but the nature of trainee selection, classification, and placement systems also plays a major role in overall cost effectiveness. Thus, these non-training factors must and will be an integral part of training system design in the future.

Training Technology

During the years since World War II there has slowly evolved a real technology of training to include a set of guidelines and procedures that underlie the development and implementation of cost effective training systems. Several major dimensions of this technology can be identified. First, the techniques of job/task analysis and instructional systems development (ISD) have significantly affected the content and nature of training, as well as what it is that we measure to determine training progress and job proficiency. Too often in the past, the contents of training programs and performance measures have been determined by the idiosyncratic opinions of various "experts," or simply by the inertia of tradition, rather than by systematic analysis of the requirements of the job. The result often has been training programs that contained substantial amounts of material unrelated to the job requirements and/or programs that omitted material and skills that were critical to job performance, as well as measures of performance that did not reflect real job skills/knowledge or proficiency. Such programs then necessarily placed an undue burden upon on-the-job training and job experience as a means of producing the knowledge and skills required for successful job and mission performance. At the same time, our attention to on-the-job and continuation training has been sporadic and non-systematic, with the result that such training often has been inefficient at best, or ineffective at worst. These inefficiencies are costly in both financial and mission performance terms and cannot be tolerated in the future. Job/task analysis, ISD, and performance measurement technologies provide effective means of reducing significantly such inefficiency and ineffectiveness in training system design and operation *if these technologies are given appropriate priority and support.* While the year 2020 will see a new generation of Air Force officer and enlisted personnel in place, a group that will be well-attuned to much of the new approaches to training discussed here, the critical importance of continuing high level command support for such approaches cannot be stressed too strongly.

A second major underpinning to the emergence of a real technology of training has to do with the developments in cognitive science generally, and in the psychology of learning specifically. Training programs typically have been developed in the past with relatively little attention paid to the nature of the material and skills to be learned as they relate to the fundamental

characteristics of the human learner, to how he/she perceives and organizes information, to valid models of human skill/knowledge acquisition, and to how training can best build on such models. Further, the schedules and regimens that best support the maintenance of skills and knowledge in a state of readiness to perform operationally have been little understood. Cognitive scientists now are developing valid models of these processes that will allow their management and manipulation in more proactive and constructive ways in the design of training programs and equipment in the future, as well as providing a basis upon which selection and job placement can build. These human models not only aid in the development of realistic and effective simulations, as discussed in the following paragraph, but in the development of intelligent tutors that will make the instruction of cognitive skills and knowledge far more effective and efficient. These developments, along with those of job/task analysis and ISD as discussed above, offer the possibility of significant increases in the effectiveness and efficiency of training by the year 2020.

The third major development underlying the technology of training is that relating to the phenomenal growth that has occurred in computer technology and use, particularly in simulators and other devices, and in the various computer-related technologies such as image generation and display, database development, and virtual reality. The increases in computing speed and data storage and handling, coupled with the orders of magnitude decreases in computing costs that have occurred over the last decade, now allow training and personnel selection applications that could only be dreamed of as recently as 25 years ago. The effect of this computer revolution has been greatest in the field of simulation, both the simulation of vehicle/weapons systems and the simulation of other functional systems (e. g., logistics), as well as simulation of the battle process itself, along with the human and command interactions that are part and parcel of that battle process. Several factors have limited the applications and full acceptance of simulation by Air Force trainers and commanders in the past, principally those having to do with the fidelity of the simulation (i. e., its ability to represent all the critical environmental, tactical, and system parameters in real-life fashion), and the cost of the simulations and the devices that enable them. Solutions to most of the technical problems relating to fidelity are within the reach of current technology, and those that remain will likely be well in hand by the year 2020. By that time, not only will we have simulation devices and programs that faithfully reproduce the environmental, situation, vehicular, and interactive stimulus-response elements necessary to efficient learning and practice, we will have the ability through networking to link such devices and programs together interactively on a world-wide basis. This also will allow an effective means of providing rehearsal for specific missions, as well as a means for providing effective joint and coalition force training. Further, the dramatic reductions that have taken place in the costs of simulation systems will continue and make the widespread use of simulation as a primary means of Air Force training a matter of routine by 2020. As a consequence, training and readiness will not be restricted by flying hour programs to the extent that they are now. The result of the advances that computer technology will allow in 2020 will be training simulation systems far superior to those that have characterized past Air Force activities, systems that will be both affordable and significantly more cost effective in meeting training and proficiency maintenance requirements. These same computer developments will allow development of personnel selection and performance measurement systems that will be major advances over those of the present time.

Some General Considerations

The preceding discussion makes certain assumptions about the maturity of training technology by the year 2020. None of these assumptions concerning the general capabilities that relate to training and other human system considerations would seem to be a long reach for the current technology. Most of the capabilities assumed represent an orderly outcome of developmental projects and directions that exist now and that show high probability of fruition over the next quarter-century, assuming their continued Research & Development (R&D) support. The human systems described will be primarily the result of evolutionary development and will represent relatively little that is fundamentally new or different. It can be argued that virtual reality represents a quantum leap forward in simulation capability through its ability to immerse trainees in a realistic training or operational environment, but, in truth, it is more of an evolutionary extension of various simulation and visual scene display techniques that have existed for many years. Much nearer to a revolutionary change in simulation and training technology will be the maturation of distributed interactive simulation (DIS). This will allow truly interactive, multi-player, mixed-force training for the first time in an effective and affordable way. Perhaps of most concern to us, however, should be *how we plan to use the capabilities that these developments present.*

The question of *how to use* simulation or virtually any other aspect of training technology is critical to our future programs and their cost effectiveness. Reference has already been made to past slowness in the implementation of that which is already known and demonstrated in the simulation field. The climate in the Air Force appears to be changing significantly for the better in terms of the acceptance of simulation and other "new" training techniques and motivation to utilize to real advantage that which those techniques offer, but there is still some question in that regard as it relates to the capabilities of Air Force training in 2020. *Realizing the full potential of human system design will require that training and human factors be accorded proper priority in Air Force system management, R&D programs, and funding.* If the human factors areas continue to receive low priority as in the past, the potential that they offer for the future will not be realized. Likewise, the Air Force must make a strategic choice between concern over protecting flying hours as the only *real* way to train (or flying hours just for the sake of flying) and a concern over choosing the most effective and affordable means of meeting training and proficiency maintenance requirements whether that involves flying or not.

A View of the Future

In seeking to develop a view of what future Air Force training will look like, it may be useful to revisit a conceptual overview of training that was first advanced in the SAB Summer Study of 1992 that dealt with Global Reach/Global Power. That concept represented training as being somewhat like a pyramid, with three general levels or types of training comprising the structure of the pyramid. At the base level of the training pyramid are those activities aimed principally at individual skills training, including both initial qualification and advanced levels of skills and knowledge. Much of the existing training technology R&D has been aimed at this level. At the mid or intermediate level are the training activities that focus on developing interactive and unit-level skills and performance. R&D aimed at this level has been much less prevalent (and less successful) than has that aimed at the base level of the pyramid. Finally, at the top or apex level of the pyramid are those training activities that are concerned with the

employment and management of forces or force elements. R&D (and, unfortunately, training itself) at this top level of the pyramid has been virtually non-existent. As a result, joint force coordination and management skills/experience have been found to be deficient or even totally absent.

Thus, as we seek to develop a view of future Air Force training, it should be kept in mind that we know a great deal about how to improve training activities at the individual skills level, somewhat less at the interactive and unit skill level, and much less at the top force management skills level. In the following discussion, we treat only aircrew training and maintenance training, but these topics should be viewed against the backdrop of the training pyramid concept just described. By far, the Air Force's greatest need for improving its future training system is that represented at the top level of the pyramid. The numerous retrospective examinations of past combat experience are almost unanimous in agreeing that lack of training and experience at that level likely has been the most significant deficiency in our training system. Recent reviews of the Gulf War (Desert Shield/Storm), for example, *The Generals' War* by Gordon and Trainor,[1] are replete with examples of ineffective or non-existent coordination, lack of plans and training, and unproductive actions that occurred both inter- and intra-service, as well as between US forces and those of our coalition partners. Such problems must be avoided or minimized in the future.

Aircrew Training

As previously suggested, Air Force training in the year 2020 will be clearly recognizable in terms of its genetic relationship with the past. As now, it will consist of combinations of conventional classroom instruction, various forms of computer-based or computer-assisted instruction, various simulation devices and programs, actual in-flight instruction and practice, and even use of "old fashioned" paper materials. But, unlike today, the computer will be central to virtually all training, and training will be much more decentralized, occurring largely at the home operating base rather than at central schools, except for initial qualification training. Distance learning will be routine. At the same time, distance learning technology and intelligent devices will allow training to be portable and capable of deploying to the field with the operational unit. The advantage of this portability of training to maintenance of proficiency and to mission rehearsal at remote deployed locations cannot be overestimated.

Training will be a much more targeted and precisely managed activity in terms of its content and its outcomes. It will involve a much more productive pairing of trainee capabilities and instructional programs with training outcomes and job performance. Training and operations will become a highly individualized and integrated system, virtually seamless in nature, which will at once recognize the idiosyncratic learning and performance capabilities of the individual, the training requirements, and the mission goals. Further, training will be concerned not just with producing skills, but also with producing positive attitudes and motivation. The effect of these changes will be analogous to the increases in mission effectiveness and efficiency that have occurred through the introduction of precision guided munitions. Precision guided training (PGT) will produce a similar increase in performance of the *training mission* and,

1. Gordon, M. R. & Trainor, B. E. (1995). The Generals' War: The Inside Story of the War in the Gulf. Boston, Toronto, London: Little, Brown and Company.

ultimately, of the *operational mission*. PGT has the potential for reducing training costs by as much as 50% and training time by perhaps 30%. More importantly, however, increases in mission performance of up to 30% may be possible through PGT. Cost effectiveness of training programs and devices will be a major concern and will be demonstrably and significantly improved over previous practices.

Initial qualification training for aircrew personnel will be similar to today's training, occurring at central schools, but likely of shorter duration and with more imaginative uses of simulation and other computer-based media. The Joint Primary Aircraft Training System will be fielded as the new training aircraft and simulation devices with high vehicle and environmental fidelity will allow ground-based learning of virtually all contact and instrument flight maneuvers, as well as basic combat maneuvers. Knowledge instruction will depend on a variety of computer-based training media to include intelligent tutors and personal work station devices. All training, to include the scheduling of facilities, aircraft, and maintenance, will be under control of a computerized training management system (TMS). The TMS will establish individualized training schedules and regimens for each trainee that recognize the unique aptitude and capability profiles of each trainee, trainee progress to date, learning requirements of new material to be trained, and the availability and cost effectiveness of training facilities and resources. As a result, while undergraduate level aircrew training will bear considerable resemblance to today's training, it will be a much more effective and efficient activity.

Continuation training and proficiency maintenance in 2020 will rely much more heavily on simulation and much less on actual flying time than is presently the case. It will be possible to produce an aircrew performer who is demonstrably superior to that of today for virtually the full range of operational requirements almost entirely through the use of simulation. In fact, simulation will be not just the *only affordable* or *most affordable* means of meeting most training and proficiency requirements, it will be the *only* means of meeting a great variety of such requirements, many of which presently go ignored or untrained.

Significant changes will occur in system qualification, mission qualification, and continuation training programs, with the computer and simulation playing greatly expanded roles. Training for adversarial air combat encounters will be highly realistic, involving multi-player, many-vs.-many training with realistic visual world displays (involving extensive elements of virtual reality) and databases that will allow reproduction of the world-wide operational environment. Field-of-view, brightness, and resolution problems in visual displays will have been solved by 2020 through helmet-mounted displays and virtual cockpits. Three-dimensional viewing is likely through stereoscopic presentation, and perhaps through holographic displays. Adversarial opponents will be intelligent and interactive combat elements, consisting either of elements manned by other live trainees or expert "Red Force" operators, or of intelligent computerized automated elements.

Probably even more profound changes will occur with reference to joint-force and coalition training through the widespread use of DIS technology and satellite linkage. Mixed force elements, to include Air Force, Army, Navy, and Marine Corps (or coalition partner) elements, will be able to engage in major force-on-force training exercises against intelligent and realistic enemy force elements, all the while without leaving their home stations. Such training will involve combinations of air, ground, and sea vehicle simulators, other devices, real ground, sea,

and air vehicles, and a variety of computerized battle management or virtual adversary elements. Combat outcomes (kills, battlefield interdiction, bomb damage) will occur in interactive real-time fashion during such training and automatically will be recorded, scored, and available for further analysis and real-time feedback and use in training. While this marriage of simulation with distributed networking will represent something of a revolution in training methodology, one that will produce significant increases in operator proficiency and in force readiness, it does not represent radically new technology. Rather, it represents a maturing of several technologies and their combination in a natural evolution from old fashioned battle and command-post exercises and their more modern Red Flag air combat exercises. These same technologies will offer the means to address the training needs at the top level of the training pyramid as discussed earlier.

The availability of world-wide terrain mapping, atmospheric, and environmental databases in 2020 will allow the high-fidelity simulation of specific missions for operations in any part of the world. This capability, in combination with national intelligence assets, will represent a real revolution in the Air Force's ability to prepare for and execute specific missions in timely fashion. The reduction in size (and cost) of various simulation devices by the year 2020 will allow such mission rehearsal preparation to take place at any operating location in the world. Thus, aircrews can prepare for missions with a thoroughness and effectiveness never before possible. The benefits of mission rehearsal may be greatest in coming years for special operations forces, but mission rehearsal will also produce significant increases in effectiveness of execution for all Air Force missions, whether they be combat, peace-keeping, or humanitarian missions into known or unknown environments and locations.

This greatly expanded reliance on simulation is not meant to suggest that actual flying of aircraft will be unimportant to training by the year 2020. That outcome will not exist as long as we have manned aircraft systems. (It can be argued that there are no unmanned systems, all systems being under human control at some level. Whatever their nature, simulation will play a significant role in the training for virtually all future combat systems.) But, by 2020 actual flying will be more of a final *confirmatory* phase of aircrew training that will validate the training and learning that have occurred on the ground. *Learning, as a process, will take place primarily on the ground through simulators and other devices rather than in the air.* As a result, the aircraft in flight will no longer be the locus of most initial learning experiences. Those experiences can be given much more economically, and usually more efficiently, on the ground. However, in-flight training will continue in some degree. It will be possible, though, (and necessary because of budget and airframe aging) to use flying hours more productively than in the past. This will occur, in part, through better planning and program design, but also through use of on-board simulations (or system simulations). In this way, even real mission time or time in transit can provide a richer in-flight training experience.

Expanded and more effective and realistic versions of Red Flag-like exercises will be developed for use in 2020. Release of flying hours, through the use of simulation and other devices, from the burden of supporting much of the initial learning experience and proficiency maintenance will allow more aircrew personnel to participate in Red Flag exercises and to do so more frequently and productively than has been possible in the past. The instrumented ranges used in Flag exercises will be more capable than at present in terms of their combat fidelity and currency of threat representation, their portability (to take advantage of different geography),

performance recording and evaluation, and general realism in representing various combat environments.

The net result of this creative use of a variety of training technologies in 2020 will be a significantly better-trained aircrew, an increase in operational mission capabilities, a significantly higher degree of force readiness, and an affordable and cost effective training system. It also will effectively help extend the life timeline for the aging aircraft fleet further into the future by lessening the demand that training will make on the finite pool of aircraft flying hours. As has been noted in previous SAB studies, there is a pressing necessity that Air Force training be viewed in a total tooth-to-tail system context (i.e., that there be a seamless integrated approach from the first day of the trainee's career (or even prior to that in his/her selection) to the last day of service), and that all aspects of human systems and interfaces be given appropriate consideration (e.g., selection systems, cockpit design, C^4I, etc.). Training and manpower costs represent a major cost driver in Air Force budgeting, and it is only through the total system approach that such costs can be kept within reasonable bounds *and* still allow the production of an effective combat ready force.

Maintenance Training

Much of the preceding discussion has been oriented toward the training of aircrew personnel. Such training, of course, is a prime concern of the Air Force, and it warrants every consideration and the best technological support. However, the training of other Air Force specialties, particularly those having to do with aircraft maintenance, is equally important. In fact, if one considers the increasing tendency to automate aircrew functions, and even the possibility of removing the human operator from the cockpit for some systems, the demand for, if not the importance of, certain aspects of aircrew training may decline significantly in the future. Regardless of the nature of future air vehicle systems—manned/unmanned, automated/manual—they will have to be maintained if an operational capability is to continue for the Air Force. It could be argued with some credibility that maintenance is potentially the Achilles' Heel of the Air Force. The knowledge and skill requirements to maintain modern aircraft systems are increasing at the same time our maintenance manpower resources are declining. As noted previously, the Air Force trainee of 2020 will represent a bright and highly capable human raw material. The training system must be geared to make best use of those human resources in the next century, whether in aircrew or in non-aircrew jobs, if an operationally effective force is to continue.

The nature of the maintainer's job, as with that of the aircrew, is in process of significant change. The effects of the two-level maintenance organization may be profound, as will the reduction in the number of aircraft maintenance specialty codes. At the least, these changes will result in a necessity that the maintainer have a broader variety of skills than in the past. In addition, the interactive complexity of aircraft systems, along with the increasing use of computers in aircraft, greatly magnifies the need for diagnostic and troubleshooting skills. Such skills have traditionally been among the most difficult to teach and often develop only after long years of on-the-job experience. Fortunately, the evolution that is occurring in training technology will also aid the maintenance technician of 2020 in the training, development, and maintenance of diagnostic and troubleshooting skills and in his/her job performance. As aircraft are modified and retrofitted, there will be increasing use of built-in-test technology, smart

materials, and the like, and the move toward a paperless tech order environment and the use of major job performance aids will also help the maintainer. The Integrated Maintenance Information System (IMIS) and its successors will be in general use by 2020, thereby vastly simplifying the maintainer's job by serving as a highly versatile job performance aid, perhaps even bringing a type of artificial intelligence to bear on the problems of fault diagnosis and troubleshooting. Intelligent tutors will also be in widespread use in operational units and will serve as a principal medium for maintenance training. There will also be an increase in the versatility, through the use of Virtual Reality, of more complex maintenance simulation devices used at central schools during the initial and advanced qualification training for the mechanic. IMIS itself (or its progeny) will also function as a training device, both at the initial training level and in the field. As with aircrew skills, maintenance training must treat requirements at the top level of the pyramid, to include logistics and transport requirements.

While the criticality of the maintenance function will increase dramatically over the next quarter-century and the manpower resources will decline, the outlook for effective applications of advanced training technology to maintenance training requirements is encouraging. But, the Air Force can ill afford to continue to rely on its rather unstructured approach to unit on-the-job training, as has largely been the case in the past, as the means of meeting those needs in 2020. If it is to remain an operationally viable and credible force, the Air Force must give maintenance training priority and support it through the best that training technology has to offer.

The Journey to the 21st Century

The view of the future for Air Force training depicted here is a rosy one. It foresees training that will be rather precise in controlling outcomes and that will produce a significantly more effective combat force than exists today. Further, training in 2020 will be more cost effective than ever in the past, assuming equality of combat proficiency. But, as stated, combat proficiency will not be just equal to that of the past, but significantly advanced through the superior training regimens of the future. This is not to suggest that there will not be a price to pay to achieve these results. There will be, and it will not be insignificant. However, if present training practice (with its emphasis on in-flight training) is continued, the price in dollars will be even higher, and the price in lost combat performance would be incalculable. While we might be able to afford the fiscal cost, we cannot afford the combat cost.

As was stated earlier, achieving the cost effective training system envisioned here will depend on the maturation and application of a variety of aspects of training technology. The development of these technologies is well underway in the various Air Force, other service, and industry R&D laboratory programs, and the probability of their successful maturation over the next 25 years is high. However, their success is contingent upon their being accorded proper priority and funding support and, perhaps of even greater importance, upon the clear recognition by Air Force management that human systems are critical to all future operations and capabilities. Human systems technologies (including training, selection, and hardware/software system design) likely present the highest potential for leveraging available Air Force resources so as to enhance operational capabilities and combat potential in these coming years. Leveraging through optimized human systems design will probably produce greater operational gain than even will new aircraft and weapon systems, particularly when one considers the fiscal climate that will exist over these coming decades. The cost of considering human systems is affordable; the cost of ignoring them is not.

Appendix J

Modeling and Simulation: The Human Factor

Introduction

Within the next 50 years or so, terms such as "human-machine interface" and "human-computer interface" may no longer have meaning in the current context, except perhaps for historical purposes. The familiar concepts of "decision aids," "data fusion," "situation awareness," "information overload," "human-in-the-loop," and the like, will be replaced by "warfighter/battlespace fusion," and "neural internet nexus." "Virtual reality" will be surpassed by a new reality. Issues currently surrounding the difficulties and challenges of modeling or simulating (or even understanding) human behaviors, functions, performance, memory, thought and decision processes, and the factors that affect them, should have been overcome or solved by having taken a different approach to integrating these questions into our machines and computer systems designs. That approach will not be the engineering approach of decomposing these kinds of questions and issues down to the smallest component levels before tackling an understanding or solution set, but rather a systems architecture approach that would enable the design of a *system*, totally integrating the human and the machine, so that the two together become an entirely new type of entity.

This paper offers a futuristic vision of the ultimate aimpoint for technology research in modeling and simulation of human systems issues (e.g., training, performance, decision making). Given the current approach of incrementally pushing back frontiers of science and engineering, the most difficult hurdles to overcome in achieving this future will be cultural rather than technological.

Application of Modeling and Simulation

It is important that we periodically remind ourselves that computer models, simulations, simulators, and virtual reality systems are tools that we invoke to help us understand or imitate the world around us. The degree to which these systems match that which they are created to represent is a function of their purpose or application, the resources available to create them, and the technology constraints in effect at the time of their design and construction.

When all fiscal and technological constraints are removed, one can assume that our models could be made "perfect," i.e., indistinguishable from that which is being modeled. In other words, in the future it will become possible eventually to create "reality" if enough resources are committed to doing so. Periodically, a moment spent in reflection on the implications of this kind of future, as illustrated in Figure J-1, will be time well spent.

For applications of models, simulations, simulators, and virtual reality systems in Air Force training, current technical issues such as latency, fidelity, and interoperability must be examined carefully with regard to the increased effectiveness of training or the enhanced performance provided by each incremental advance that technology will provide. In other words, training systems should be designed *to produce the conditions necessary for training* and *sufficient for training*. The cost to the Air Force of pushing simulation technology beyond the point where

technical advances provide measurable improvements in training would be incalculable. The admonishment is to avoid allowing technology to drive the shape and contents of our toolkits, which in turn could shape our training philosophy and programs. Rather, training needs should drive the shape of our training tools, and thence the technologies that support those tools.

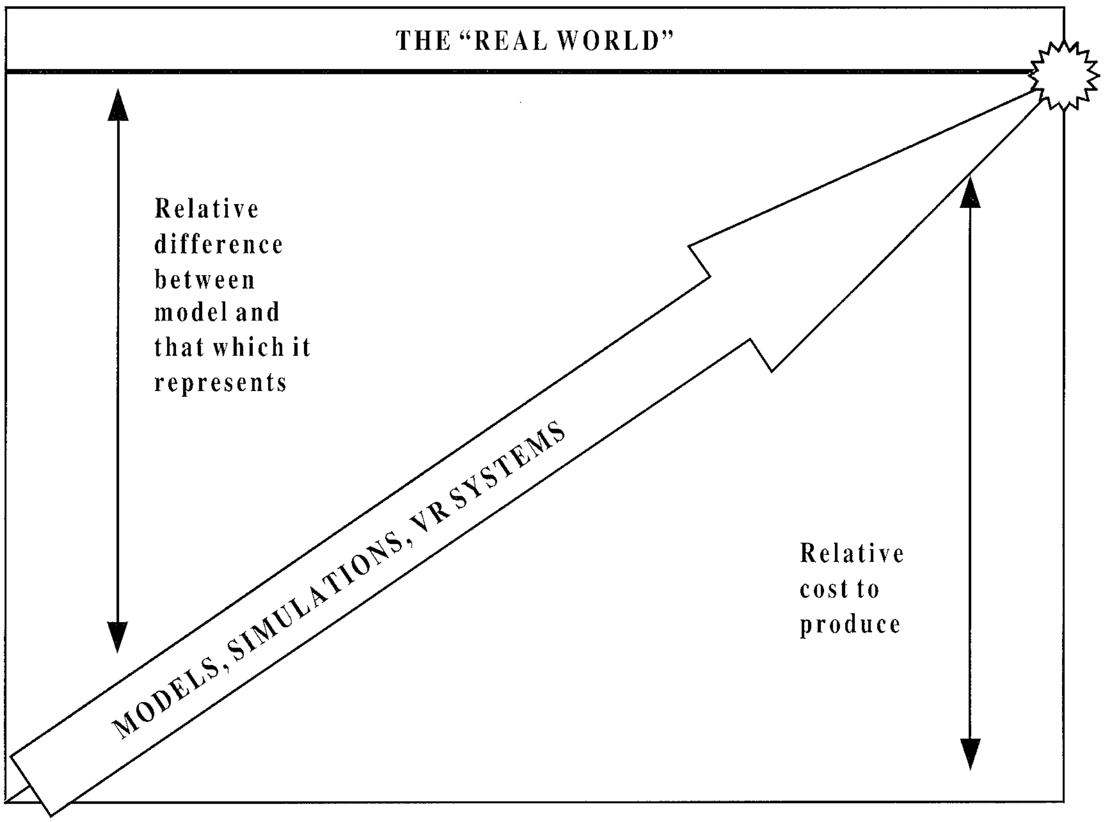

Figure J-1. Fidelity vs. Cost of Modeling and Simulation

On the other hand, technology advances will allow some capabilities to explode, allowing us to do some complex things at relatively modest cost, and will make simulation devices available on a widespread basis. For example, the warfighter will be able to remain at his home station and accomplish much of his training there. And with latency and bandwidth hurdles overcome, networking via the Defense Simulation Internet (DSI) will permit the training of skills in a joint arena or in cyberspace training ranges.

By 2020, most of all real learning will occur on the ground. Aircraft exercises will serve to confirm and refine training, not serve as the primary locus of learning experiences. The benefit to the Air Force will be to yield more hours of aircraft availability for mission business rather than training, with the potential of dramatic savings in training costs.

The Modeling of Human Factors

The incorporation of human performance issues and factors into the construction of models and simulations is crucial to allowing human factors to be taken into consideration by models as they generate information for decision makers.

Assumptions:

- Human performance factors are not adequately considered in current combat models.
- There is a solid base of human performance modeling technology and data which can provide required input to combat simulations.
- We are entering an era where new types of combat models will be needed and, therefore, have an ideal opportunity to build human performance considerations into these models.
- Human performance is a variable, without question, but is not always treated as such, primarily because it is so difficult to do so. One basic question, "to what extent can existing combat models accept or be modified to accept near-term human performance factor (HPF) data bases and provide HPF-influenced output for support of decision issues?," must be addressed before a reasonable case can be made to modify existing models or to start over with something new, built with the integration of HPF as appropriate variables in the models.

Some specific areas needing more attention in the near-term are:

- Quantifying potential performance degradation of individuals and crews in combat environments, based on data from combat, weapons tests, and real-time simulations.
- Techniques for estimating environmental and workload effects on human performance and quantifying these.
- Availability and utility of human factors (performance, response, stress factors, etc.) combat data for modeling and analysis inputs.
- Approaches for including human performance factors in modeling and analysis of combat effectiveness.

As cited in "Human Behavior and Performance as Essential Ingredients in Realistic Modeling of Combat - MORIMOC III," Clayton Thomas provided the following perspective: "As combat models were first being developed, the data used to define parameters were from actual combat. As such, human factors were actually embedded within the data and, therefore, one could argue were considered. However, as the potential for higher fidelity models increased, model builders began to segregate elements of the combat environment and develop models for them separately. For example, what was before simply a combat unit became a series of equipment items and personnel."[1] Now, as requirements emerge for increased sophistication of

1. Thomas, C. Human Behavior and Performance as Essential Ingredients in Realistic Modeling of Combat - MORIMOC III

models and simulations, human performance factors must once again be accurately represented in those systems that provide information to the decision makers on systems and situations that involve humans.

Incorporating Human Factors into Human-Machine (Human-Computer) Interface Design

Some of our systems are very sophisticated, but the human interfaces are not what they could be. Considerable effort is being expended in this area. However, to progress beyond even marginal successes, the entire concept of "interface" will have to be thrown out. No matter how good the machines become or how effective the human becomes in using them, the interfacing requirement (in the current paradigm) between the two systems remains a constraint, an immovable barrier to achieving future performance goals. This transcends the "knob-ology vs. psychology" issue.

The following simple analogy illustrates the inescapable fallacy of the current approach of "improving interfaces." Consider the unmixable liquids oil and water. When added together, each of the two layers are completely independent and autonomous, but exhibit peculiar (but well-characterized) properties at the boundary (interface) between them. The boundary serves only to divide the two liquids, and will never allow the direct interaction of all the parts of the two separate layers. This is a limiting condition, impossible to overcome without invoking a different approach. When attempts to improve the interface integration are abandoned in favor of tossing in a binding agent, a colloidal suspension can be created where the two liquids now merge into one different kind of substance exhibiting totally different properties from either of the two original substances.

The point is that certain boundaries can only be pushed so far without either defying the laws of physics or adopting a completely novel approach to solving the problem. In the case of human-machine or human-computer interfaces, we are looking forward to technologies that will support "look/think/shoot" or even "think/fly" capabilities. To achieve these goals, the notion of "interface" will have to be supplanted by the concept of "human/machine *integration.*"

"Integration," in this sense, literally means that the operator and the machine will become one functioning entity, with no interfaces as we know them today. Technology advances are encouraging some to seriously consider the notion of the "cyborg warrior." And once that idea is considered to be within the realm of the possible, one can imagine that eventually the human and the weapon system will become one "blended" effectively functioning unit.

In a future world where interfaces have disappeared, the warfighter enters the cockpit, where there are no obvious control panels or displays. As he sits down, his chair will recognize him and begin to metamorphose, to wrap around him, becoming his g-suit, heads-up display, flight controls, weapon system and communications controls, vital sign monitors, ejection seat, and so forth. Special receptors will attach themselves to him to permit the warfighter only to think of an action to cause the system to carry out his mental instructions. The *interface* is no longer an issue because the human and the machine are now merged into a *system*, where the whole is greater than the sum of the parts, and the constraints previously imposed on the system by the interfaces are no longer inhibiting full performance.

Hurdles

Hurdles or barriers to progress are generally in two forms—technical and cultural. Human ingenuity knows no bounds when allowed to function unfettered by bureaucracy, politics, and a "we've always done it this way" mentality. So, a cultural change in our approach to identifying, understanding, and then solving technical problems is the primary hurdle to be overcome.

If one has a good hammer, it is a natural tendency to look for nails. In fact, when one possesses a good hammer, everything seems to take on the traits of a nail. Similarly, if a technology that has been developed to solve a specific problem has worked well in the past, it is natural to try to find new applications for the technology. We have a tendency to solve problems, or provide answers, before really understanding what the problem is, or what the ultimate need is, in order to apply those tools we understand and feel comfortable with. In effect, we often end up only addressing symptoms, without ever really digging deep enough to understand and address the root causes. Issues tend to be addressed with the preface "What the Air Force needs is a widget to ...," or "the human factors community needs to ...," or "more/better modeling and simulation are required in order to....," and so forth. One wonders if just stating what the weak link is or what the need is, in terms of solutions, already bounds the problem by framing the solution.

Another hurdle to overcome centers around the presumed need to maximize the utility of existing systems, particularly when sunk costs are significant. As an interim measure, there is merit to this approach, particularly when it is politically expedient to seek the "low-hanging fruit." But inevitably, support and funding for the "clean sheet of paper" approach, being inherently more difficult to sell, move farther out toward the horizon. It will require a great deal of farsightedness, courage, and salesmanship to effect a change of this magnitude, but it needs to happen, starting now.

Another cultural barrier to real progress in science and technology ("real progress" meaning a leap forward such as the discovery of the wheel or of electricity) is the result of centuries of research and experimentation. Until now we have reached the point of having to focus ever more narrowly on increasingly finer points of understanding. The effect of knowing almost everything there is to know (relatively speaking) is that we seek understanding and refinement of deeper details, pushing back frontiers asymptotically. This well-accepted methodology has led to the demise of the "big picture" connectivities and to a world where we think in terms of stovepipes and soda straws. In fact, recent attempts to integrate such stovepipes gave rise to the "radiator" concept, which only serves to overlay orthogonal sets of stovepipes. Connectivities and integration must begin at the top, with a big-picture view and an overall architecture from which the parts can be understood in context with each other and within the overall schema. Today's culture tends to support the opposite approach, where we are inclined to assemble our bags of tricks and try to put them all together into a sort of reverse-engineered umbrella (where the "architecture" is held together by duct tape and baling wire), in hopes of maximizing our ability to use existing tools to solve tomorrow's problems. Unfortunately, tomorrow's problems won't be solved with yesterday's tools and approaches.

Beyond cultural barriers and limitations on creativity and imagination lie real technical barriers to the Air Force's full participation in joint exercises in cyberspace. Some of these

technical issues remaining include speed of data transmission and processing (latency), lack of adequate bandwidth and lack of solutions to multi-level security requirements. These technical issues are being worked feverishly throughout the Department of Defense (DoD) and will have to be solved (or abandoned in favor of a novel approach) before significant advances can be made beyond the current capabilities in this area.

Interim Progress

At the June 1995 Four Star Summit - Review of Air Force Modeling and Simulation, it was acknowledged that, at all levels, the Air Force suffers deficiencies in modeling and simulation capabilities, infrastructure and funding. A very good near-term framework for investing in simulation capabilities was proposed. The following deficiencies were cited in all areas:

- **Vision:** lack of corporate Air Force vision (remedied at the modeling and simulation Summit review)
- **Quality:** Modeling and simulation information flow, overlap and duplication, modeling and simulation operational support
- **People:** Air Force modeling and simulation expertise, modeling and simulation manpower management
- **Infrastructure:** model and data standards; modeling and simulation representation of air and space; use of distributed simulation technology; ad-hoc funding

The Air Force vision adopted at this meeting for modeling and simulation follows: "A joint synthetic battlespace supporting better decisions and warfighting skills to build the world's most respected air and space force."[2] (One view of synthetic battlespace: simulated fighter, simulated squadron, live weapon systems, manned simulators, standard data used for analysis and training; all expertly used and supported, representing all aspects of joint warfare, reusable, interoperable, "plug-and-play." Another view: Virtual squadron playing (training) with live squadron with constructive, linking ranges and test beds with training simulators.)

This vision was accompanied by a proposed funding plan and implementation plan. For the modeling and simulation community, this meeting was a tremendous leap forward in providing an overall vision and direction for Air Force modeling and simulation and the infrastructure to support them. But, although there is much work needed to be done in this area, we must remember that modeling and simulation are only enabling tools, not an end in themselves.

Near-Term Recommendations

Having stretched the imagination beyond what is known to be possible today, one can set more far-reaching goals for research and development in support of the Air Force vision and mission. Some of the near-term objectives that are supportable within this context and within our existing science and engineering capabilities follow:

- Many of the new training ranges and battlegrounds likely will "reside" on the Internet, in cyberspace. Addressing technical barriers to making these advanced

2. Four Star Summit - Review of Air Force Modeling and Simulation, June 1995.

simulations available to planners and operators world-wide over the DSI and their C^4I systems should have high priority.

- Capitalize on rapidly evolving, open-system computer technologies and communications interoperability to link and share our diverse modeling and simulation capabilities, both within and across the Air Force, throughout DoD, and globally with our allies.
- The focus in developing new types of combat models should be placed on higher level human performance factors (e.g., leadership, cohesion, and benefits of battle experience and training), to the extent that they may affect military outcomes.
- Much research is needed to increase understanding of information processing and transmission within the human brain, leading to a breakthrough in development of "wetware" man-made hybrid biocomputers.
- Place high priority on investment in materials science research, particularly in the areas of smart skins, smart materials, adaptive cockpits and adaptive workstations. Emerging biotechnologies, such as DNA-based optronics, should be heavily supported, to promote advances in high speed data- and image-processing and other complex computing tasks.
- Research on the function of the brain is essential, at all levels from the higher thought processes, to the biochemistry of memory, to the understanding and control of electromagnetic output of the brain, and especially toward a better understanding of the mental processes and perception capabilities beyond the range of the five senses, including intuitive processes and "gut feelings."
- The Air Force, being the technological leader within the DoD, is credible and well-positioned to lead the Department into the next millennium by hastening its evolution away from the force-fit engineering mind-set regarding technological advances and toward embracing the twenty-first century culture of holistic systems research and design.

Appendix K

Unmanned Air Vehicles[1]

Introduction

Unmanned Air Vehicles (UAVs) have recently joined the deployable force structure, and doctrine concerning their use is still maturing. On 16 October 1989, the Director of Defense Research and Engineering established the Unmanned Aerial Vehicles Joint Project Office as the single Department of Defense organization with management responsibility for UAVs. Since then, UAVs have begun to enter the main stream acquisition process. Pioneer and EXDRONE UAVs flew operational missions in Desert Storm, and numerous UAV airframes are in Advanced Concept and Technology Demonstration, in production, or fielded with operational forces. UAV applications include strategic and tactical reconnaissance using electro-optical or electromagnetic imagery, real-time video surveillance, electronic warfare, search and rescue, battle damage assessment, communications, and psychological operations.

Each UAV program prepares a Human Systems Integration (HSI) Plan and identifies an individual responsible for HSI. The HSI section of the 1994 UAV Master Plan focuses largely on assessing manpower requirements. Existing skills are stressed to minimize unique requirements in the force structure. Human factors, safety, and health issues also receive analysis. Operator workload analyses are conducted, such as the one performed for the Hunter UAV in FY94.

UAV pilots face serious problems when controlling UAVs, particularly during takeoff and landing. A lack of situation awareness can also make it difficult to aim sensor platforms and deal with in-flight contingencies. The Air Force "Supercockpit" research program has attempted to use tools such as head-mounted displays (HMDs) and augmented reality to enhance the situation awareness of manned-aircraft pilots. Some of the technologies fostered by the "Supercockpit" program may be useful for UAVs, but the manner in which they are applied will reflect the fact that UAV concepts of operation differ greatly from those for manned aircraft.

The task for HSI developers is not simply to create a complete sense of presence for a pilot remotely controlling a UAV. Many tasks, such as wide area surveillance, are tedious and may not require the capabilities of a human pilot. These tasks can be automated much like tedious industrial tasks. A human exerting supervisory control can define task assignments and deal with contingencies. A continuum exists from manual remote control, through supervisory control, to "complete" autonomy. All systems, regardless of their place on the continuum, will have human factors and situation awareness challenges. The placement of a system on the continuum will be a question in itself, with different UAV airframes or missions being more suited to manual or supervisory control. Dynamic mission requirements may require that the control paradigm be shifted more than once during a mission.

1. Thanks are expressed to the personnel of the Armstrong Laboratory and especially to Capt Hasser, AL/CBFA, for providing the supporting material used in addressing this topic.

Since the end of World War II, a continuing research and development program has been devoted to enhancing and optimizing the man/machine interface in the control and operation of manned aircraft. Much less attention, perhaps due to their somewhat limited capabilities and roles to date, has been directed toward defining and optimizing the human role in the operation of unmanned systems.

With the rapid growth of computational capabilities, the reduction in cost of providing those capabilities, the world wide communication nets now available, and the significant advancements which have occurred in the micro-miniaturization of sensors and system components, the potential areas for utilization of unmanned vehicles in military missions is rapidly increasing. In looking toward new applications and mission opportunities for unmanned systems, however it can not be assumed that a direct transfer of control/display technology can be made from piloted systems to remotely controlled systems.

In light of emerging technologies and evolving mission roles, the Air Force must look beyond the next 25 years of piloted aircraft operation and begin now to direct more attention toward the research needed to define and optimize the role of the human in unmanned system operation.

Background

The basic characteristic of a remotely controlled system is that the human controller provides the vehicular control while not being physically present in the vehicle itself. Remote control is used to augment and enhance human capabilities and extend them beyond the human's physical presence while effectively utilizing human sensory and perceptual capabilities to see forms, patterns, spatial relations, and to make decisions with the flexibility to take such action as the operational situation may warrant.

Situations where remote control is warranted include those: (1) where the vehicular system is to operate in areas which are intrinsically hazardous to the human due to hostile fire, ionizing radiation, biological or chemical threats, and (2) where flexibility of operation is required, but the mission contains elements such as high accelerations or severe vibrations that are beyond the human's physical capabilities to withstand even with the use of protective systems.

In the next century it can be anticipated that with the continuing growth of communication capabilities, data processing resources, inexpensive computers, and improved sensor systems the potential for the utilization of unmanned vehicles to accomplish Air Force missions will significantly increase. With this potential, the need to place an aircrew directly in harms way can be significantly reduced.

Potential applications of unmanned vehicles include:

- Intelligence gathering and reconnaissance
  - Small units (e.g., Robotic birds/bees)
  - Miniature UAV target detectors/hunters/trackers
  - Larger Tier 1, Tier 2, and Tier 3 UAVs for sophisticated reconnaissance and surveillance

- Mobility and Airlift support
  - Precision delivery with option to control delivery from ground destination point
- Weapon delivery against ground targets
- Achievement of Air Superiority
  - Unmanned air combat vehicles with close-in air combat maneuvering and beyond visual range tactical capabilities
  - UAV wingmen for support of piloted aircraft
  - Multi-ship UAV combat

While UAVs have served usefully in many applications to date, performance is highly dependent on how well man-machine interface problems are identified and resolved during the design and development phases of system procurement. Often it has been the case, especially on small low budget programs, that minor problems and human factors considerations have gone unidentified until their eventual discovery during system operations caused expensive redesign and retrofit or jeopardized mission success.

At the present time and in the immediate future, the number of Tier 1, Tier 2, and Tier 3 UAVs in operation will be somewhat limited. Even so, the potential capabilities that are represented by current developments provide some insight into what the future may hold. Tier 2 UAVs carrying a suite of electro-optical and infrared sensors have a 6000 mile range.[2] The Teledyne Ryan Tier 2+ UAV is reported to be designed to operate at 65,000 feet for 24 hours at a distance of 3000 nmi. from its base.[3] With a 116 foot wingspan it will have a takeoff weight of 20-25000 pounds. It will carry Synthetic Aperture Radar, electro-optical and infrared sensors. This vehicle will have a 48 inch satellite dish and be capable of transmitting real time imagery and video. The unit flyaway cost per vehicle is estimated to be approximately $10 million. The "Dark Star" Tier 3- Unmanned Aerial Reconnaissance Vehicle developed by Lockheed/Boeing is a 100 foot wide, very low observable flying wing capable of carrying a Synthetic Aperture Radar and electro-optical camera and having a loiter time on target of 8 hours.[4] The flyaway cost of these vehicles is reported to be $10-12 million each. The philosophy of operation of these vehicles is to allocate high risk, low value tasks to the unmanned adjuncts and to reserve people for the high value, very difficult tasks. At the present time Tier 2+ and Tier 3- vehicles will use the same ground support stations.

Extrapolating from today's state-of-the-art it can be anticipated that the capability will exist by the year 2020 to field a force of unmanned aircraft capable of performing almost all of the tasks being performed by today's Air Force and to do so at a cost per vehicle comparable to, or less than, that experienced with today's aircraft. This would include reconnaissance, surveillance, airlift, air-to-ground weapon delivery, and air-to-air combat missions.

The point of concern is that while hardware technology advances to support operational requirements, it is mandatory that equal attention be given to the design of the human interfaces.

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2. Aviation Week and Space Technology, Jan.9, 1995.
3. Teledyne Ryan Team Wins Tier 2+ UAV Competition (1995, May 29). Aviation Week and Space Technology, p.26.
4. Aviation Week and Space Technology, Sept. 19,1994, p.27.

The system is only as effective as the weakest link and proper attention to the design of the human requirements in terms of information displays, controls and the human working environment is needed to insure that the weakest link is not the human element.

Issues of Concern

A number of human factors areas must be considered to insure the efficient and effective utilization of human capabilities in operating remote viewing devices in particular. Foremost among these are human perceptual and visual capabilities and their interaction with the image presentation and the acuity tracking subsystems. These subsystems must be designed to minimize the weaknesses in the human visual and perceptual capabilities and to take advantage of their strengths. Items of concern include: static factors such as brightness, resolution, field of view; and dynamic factors such as system lags or delays and tracking techniques. Early identification of the optimal role of the human controller will highlight the technological gaps that need to be filled in order to meet the mission objectives in the most cost effective manner.

Information display systems and concepts designed for piloted aircraft may not necessarily be the most effective for the remote control and operational utilization of UAVs. As pointed out earlier, the remote control of a moving vehicle can be confusing depending on whether the vehicle is coming toward the operator or going away from the operator. For this reason, some UAV operators have had serious problems when controlling UAVs, particularly during takeoff and landing. As another example, in cockpit navigation displays, mapping information is presented in either a "Track up" mode or a "North up" mode. In the former, flight control is simplified in that all turns are either to the right or left of the heading and information presentation is "egocentric" in format. Unfortunately, the rotating display hinders the development of an "exocentric cognitive map" by the remotely located UAV pilot so vital for complete situation awareness. On the other hand, the "North up" display aids in the development of the UAV pilot's cognitive map, but complicates the pilot's aircraft control process and when flying in other than a northerly direction can result in errors and incorrect control actions. If the vehicle were being controlled from a remote location, a "top down" or bird's-eye (big picture) display might be more effective. In other cases a trailing view (as though the operator were flying behind the UAV) might be the most effective. The point at issue is that the optimal display for the remote controller may be quite different than that required when control resides in the cockpit of a manned aircraft.

Computer generated imagery and display systems to create "virtual realities" have been applied to simulation training. It has been suggested that technology can extend this concept of virtual reality to the design of vehicle control systems so that the pilot would control his vehicle in the same manner whether he was in the cockpit or in a remote location. Unfortunately simulators which receive the highest marks for realism from experienced pilots also score highest on simulator sickness incidence. Locomotor ataxia, interference with higher order motor control, physiological discomfort, and visual after effects have been reported.[5] Problems also occur with flicker, distortion, cue asynchrony in the inertial environment (especially if there is a mismatch

5. McCauley, M. E., and Sharkey, T. J. (1991). Spatial Orientation and Dynamics in Virtual Reality Systems: Lessons from Flight Simulation. In Proceedings of the Human Factors Society 35th Annual Meeting, (pp 1348-1352). Santa Monica, CA: Human Factors Society.

on the order of 0.2 Hz). While these problems are not as significant in the training environment, they could be critical to mission success or failure in an operational situation.

The idea of creating a virtual reality, transparent to the mode of operation, wherein the human/machine interface is the same whether the human is in the cockpit or in a remote location is an intriguing one. In reality, however, optimization of the vehicular interface may require that very different psychomotor and perceptual relationships be established to optimize control in the different situations.

The optimal degree or extent to which telepresence is required will need to be defined. The term telepresence reflects the completeness of sensory inputs, sensory motor coordination and feedback to the extent that the operator "feels" present at the remote vehicle. Typical research questions that arise will ask: To what degree does a feeling of presence actually enhance performance? What is lost when force feedback is presented visually or aurally rather than kinesthetically? Are there more important variables to which research should be directed that are more likely to improve performance than "telepresence"?

To a great extent the creation of telepresence requires the capability to display apparent movement of the operator through visual space. The display incorporates both translational and rotational movement and the visual dynamics of the display system become quite critical. Digital image generation coupled to advanced display systems with a wide field of view are improving rapidly in resolution and quality. The purpose of such systems is to convey a sense of self movement via the optical flow. Dynamics seem compelling and virtually real to the user. In such computer generated systems it is possible to introduce spatial and temporal distortions. The rate of global visual flow can be reduced by moving through the displayed environment at higher altitude or at lower speed or both. It is essential that any system intended to produce illusory motion (e.g., virtual reality systems) should minimize temporal differences between user control outputs and resultant changes in the display and between sensory modalities (e.g., visual and vestibular).

The fidelity of the information displayed, the refresh rates of the displayed information, and the dynamics of the control responses are important determinants of performance in any situation, but are especially critical in remotely controlled operations. In teleoperated tasks, the mean task times take significantly longer as the frame rates of video display decrease.[6] Tasks performed at three frames per second took twice as long as the same tasks when the frame rate increased to 30 frames per second. Force feedback in the controller was also found to be beneficial in teleoperations. Mean task times doubled without the use of force feedback, and force feedback was found to make up for slow framing rates. In one study with force feedback, task performance was as good at three frames per second as it was at 30 frames per second with no force feedback.

Introducing aids in the form of automation eliminates some tasks but creates new ones associated with programming, engaging, disengaging, etc.[7] In some cases, the burdens of managing automation can outweigh the potential benefits. Loss of "situation awareness" is a very

6. Massimino, M. J. & Sheridan, T. B. (1994). Teleoperator Performance With Varying Force and Feedback. Human Factors, 36(1), 145-157.
7. Kirlik, A. (1993). Modeling Strategic Behavior in Human-Automation Interaction. Human Factors, 35(2), 221-242.

real possibility if the human operator is not actively in control of the vehicle or if his attention is diverted from continuously monitoring the present state of the vehicle. Operators must know how their system works and must have an appropriate mental model of the device they are controlling and the environment in which they are operating. Present day Flight Management Systems (FMS) can be programmed to automatically control aircraft from takeoff to landing. Unfortunately, critical incidents and accidents have occurred where inadvertent FMS mode settings and selections did not immediately produce visible consequences and were not noted until the situation became critical.[8] Relying completely on automation can complicate the process of error or fault detection and creates the possibility of the operator committing "errors of omission." A further complication arises in the maintenance of "situation awareness," in the operation and control of the system, when multiple operators are involved and have complementary or overlapping tasks to perform.

New battle management systems automate more functions, track more data, and provide more operator options. When automation is introduced into vehicular control, however, it drastically changes the nature of the operator's task. It requires new skills. New tasks are created, such as that of data base manager. Again, the effect of automation is not necessarily a reduction of workload but rather a displacement of workload. In the past, evaluation techniques employed to investigate the performance impacts of increased automation and enhanced system capability have been applied too late in the design process to truly influence design. Attention to the human factors issues must be given in the conceptual design phase if the man/machine interface is to be truly optimized.

When "expert systems" are used as a part of the mission operation, the "expert system" should focus the operator's attention on where it is required the most. When this is done however, the result usually leads to inferior performance for less critical yet important tasks that also require the operator's attention.[9] Human information processing capabilities are not well suited to a multiplicity of simultaneous and disjointed tasks.[10] People can consciously think about only one thing at a time. As a result they do not handle interruptions and distractions very well. Choosing to focus attention on one set of events can be achieved only at the cost of diverting attention from all others. The expert system interface must give operators time to assess the situation and select the specific cases that they, the operators, wish to consider.

With the introduction of UAVs, new strategic plans for combat will be required. Complex environments will present serious challenges in the development of means to evaluate performance. Air to air combat using remotely controlled vehicles will be especially complex. Tactical air combat maneuvers, multi-ship air combat, close-in air combat maneuvering and beyond visual range tactics, will all present new problems to be addressed. These problems will not only impact system design but will define training processes and simulation requirements as well.

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8. Sarter, N. B & Woods, D. D. (1995). How in the World Did We Ever Get into That Mode? Mode Error and Awareness in Supervisory Control. Human Factors, 37(1), 5-19.
9. Adelman, L., et al. (1993). Real-Time Expert System Interfaces, Cognitive Processes, and Task Performance: An Empirical Assessment. Human Factors, 35(2), 243-261.
10. Adams, M. J., Tenney, Y. J., & Pew, R. W. (1995). Situation Awareness and the Cognitive Management of Complex Systems. Human Factors, 37(1), 85-104.

Certain design constraints for the operation and control of unmanned vehicles will undoubtedly continue into the foreseeable future. Electronic and electromagnetic signatures must be kept to a minimum. Independent channels of communication for different vehicles must be maintained. The amount of information that must be transmitted between the vehicle and the control station will be constrained. The field of view available to the controller may be restricted. Unless the potential problems with the creation of displays to provide a virtual reality can be resolved, the 3-D world may continue to be portrayed on 2-D displays.

Future operations with unmanned vehicles will involve some mix of teleoperation and supervisory control. Through teleoperation the system operator will use remotely controlled sensors and actuators thereby allowing the human presence to be removed from the vehicle or work site. In many cases direct control of the system operation, whether by manual input or by teleoperation, will be supplemented or replaced by computer-directed functions which maintain the commanded state of the vehicle (altitude, attitude, heading, speed, weapons delivery mode, etc.). Also many tasks, such as wide area surveillance, are tedious and may not require continuous human monitoring. In this latter case, the human role most likely will be to function in supervisory control of the overall operation, defining task assignments and dealing with contingencies as they may arise.

Various degrees of supervisory control will be required depending upon mission objectives. Furthermore, it is very likely that mission requirements may require the operator to function in several different roles during the different phases of a mission. Workstations for different missions may vary in size and complexity and capability. Time delays in transmission and receipt of command signals will have to be compensated for. Breaks or loss of communications could result in catastrophic mission failure and some degree of self-healing and self-actuation capabilities will be required to be incorporated into the systems. System failure detection aids will be mandatory. Voice control and voice feedback may be useful.

A study of the human role in remotely controlled vehicles should consider potential technological growth in data processing capabilities, sensor resolution, component miniaturization, and communication and navigation capabilities and should identify technology gaps that may exist in meeting potential mission requirements. In this regard, it should be noted that the use of human-in-the-loop simulation can be of great value in the areas of problem identification, systems optimization, technology needs and procedures definition. Simulation can be very useful in integrating human factors into vehicle design through:

1. Determination of system capability
2. Optimization of system parameters
3. Determination of task loading
4. Establishing the impacts of transmission lags on mission success
5. Establishment of operational procedures
6. Verification of system performance

Assertion of Air Force Capability in 25 Years

Concept: Optimal UAV operation will require excellent situation awareness, with respect to the environment, vehicle orientation, and sensors. An effective user interface will allow the user to seamlessly move along the continuum from remote manual control to fully autonomous control. The operator will have a 3-D view of the virtual or real environment, either with shuttered glasses or with a HMD. In a "big picture" view, the operator will see the operating range in 3-D, with a scale image of the UAV flying through the virtual environment. The operator will see "flashlight beams" projected from the virtual UAV that represent the scan areas of the sensors. The virtual environment will be either a computer simulation of the real environment, a representation of previously captured sensor data, or a combination of the two. Virtual terrain will be color coded by sensor type, age of data, or some other criteria, so the operator can select areas that should be scanned or rescanned. The interface will also include a 3-D pointer.

Advances in human interfaces for vehicle and sensor control will also extend to the customers and to data exploitation. Knowledge will have to be gained of what should be presented to end-users to give them adequate situation awareness at the strategic and tactical levels. In some cases, intuitive interfaces will allow information customers to retask UAVs and aim sensors in real time.

Scenario: A contingency arises requiring that international observers be rescued by force and safeguarded until extraction can be accomplished. Local terrain and man-made structures make it difficult to reach the target and easy for the defenders to operate. Due to the unexpected nature of the crisis, no current intelligence on the target exists, though it is a seven hour UAV flight away from an overseas UAV operating base. Crucial satellite assets have been redirected to cover another emerging crisis and are not available immediately. The situation requires an armed response in under 24 hours.

00:00 — National Command Authority (NCA) receives notification of incident.

01:00 — NCA authorizes mobilization of ground and air strike forces, with mission go-ahead contingent on further intelligence. Theater commander requests high-altitude UAV surveillance to fill intelligence void.

02:00 — Alert HAE UAV launched.

03:00 — Strike force leaders are briefed using available intelligence. Mission planning begins. Distributed Interactive Simulation (DIS) Group begins downloading available intelligence using the Joint Collection Management Tool.

08:00 — The DIS Group finishes a model of the target area with enough time left for the players to run through at least two simulations of critical mission segments. Players include airborne troops, air strike, AWACS, UAVs, and command elements.

09:00 — HAE UAV reaches target site. DIS simulation is altered to incorporate fresh intelligence.

10:00 — NCA authorizes mission to proceed. Airborne troops take off. Transport planes have small DIS workstations on board for platoon leaders and first sergeants. Mission practice continues en route.

17:00 — New intelligence from the HAE UAV reveals a previously unknown concentration of enemy, and the airborne commander selects an alternate drop zone. Platoon leaders and first sergeants practice one simulated descent and rendezvous at the new site to orient themselves to the change in plans.

18:00 — Airborne troops jump.

18:30 — Airborne troops rally and airborne commander deploys hand-launched UAV to examine the target. This 6-foot long silent UAV reveals defenses not obvious from previous intelligence. Looking from side to side while wearing a head-mounted display so the UAV camera can track his gaze, the commander notes that the hostages have been moved from the target area and are in convoy away from the target. The ground commander requests that air strike forces destroy a bridge to block the advance of the convoy. An air strike Sensor Preview Imagery UAV arrives over the target area.

19:00 — Ground and air attack begins. The Sensor UAV provides laser spot on bridge and strike aircraft launch weapons at standoff, avoiding counter-air defenses. The hand-launched UAV loiters on autopilot over the combat area, relieving the fighting troops from the task of controlling it, and relaying real-time imagery to higher command. A medium-range UAV launched from a US Navy group operating offshore arrives on scene. It begins to jam enemy communications, provide signal intelligence, and relay information on combatants' medical condition via Personal Status Monitors on each soldier.

19:45 — Airborne commander informs higher command that the hostages are secure. The Navy UAV begins downloading real-time imagery to the airborne troops as it patrols their perimeter and main lines of enemy communication.

24:00 — Ground forces are extracted. During the extraction, an enemy Surface to Air Missile shoots down a friendly aircraft flying combat air patrol. The pilot ejects and begins evading. His presence in enemy territory gives the enemy continued leverage after an otherwise successful mission.

27:30 — After diverting the medium-range UAV, DIS technicians aboard a US Navy vessel offshore complete a virtual model of the pilot's area. While copilots command inbound rescue helicopters, the pilots link to the DIS environment and practice ingress and extraction in virtual space as they are carried towards the actual target. Though wary of unmodeled threats, the rescue pilots are able to extract the downed pilot in less time and at greatly reduced risk. During extraction, real-time updates to the DIS model allow command elements to monitor the mission.

Importance to the Air Force

UAVs employed in reconnaissance or intelligence roles enhance situation awareness on the strategic and tactical levels. They can serve as force multipliers by increasing the lethality of friendly forces or reducing vulnerability to enemy forces. In addition, extrapolating from today's state-of-the-art, it can be anticipated that the capability will exist by the year 2020 to field

a force of unmanned aircraft capable of performing each of the tasks being performed by today's Air Force. This would not only include reconnaissance, but airlift, weapon delivery, and air-to-air combat missions as well.

Threats to UAVs in flight include surface-to-air missiles and intercept aircraft. Altitude, low-observability, or small size make ground fire a small threat in most cases. HSI advances presented in this paper will enhance UAV survivability by giving operators the situation awareness to actively evade threats and by giving them intuitive mission planning tools that aid threat avoidance.

Key Technologies

UAV systems involve a wide range of technologies: airframes, propulsion systems, communications systems, sensor platforms, etc. Technologies specifically relevant to man-machine interfaces include head-mounted displays, flat panel displays, 3-D audio, and force-reflecting haptic interfaces. The accumulated base of knowledge in the areas of human factors, workload, and perception is also relevant.

Technological Hurdles

Enabling technologies for the concepts listed in this paper are already being developed, and will easily be mature enough for deployment in less than 25 years. Some, like 3-D audio, have already been flight tested. HMDs are ready for laboratory demonstrations and research; they should be ready for field use in about five years. Flat-panel displays are being pushed by large market and government forces. The key hurdle will not be in the development of enabling technologies, but in their judicious application so that they maximize the performance with respect to the "human in the loop." Some of the key questions that must be answered:

- How much do virtual reality interfaces reduce errors and workload?
- Is it feasible to give the customer direct control of UAVs and sensors?
- What is the optimum mix of human control vs. autonomy for a given mission type?
- Can a human pilot be given adequate situation awareness to aggressively maneuver a UAV in a lethal environment?

Can the Hurdles be Jumped?

The answer is "yes." A focused research effort with adequate resources could produce validated results in timely fashion to meet the needs for incorporation into the next generation of UAV programs.

Benefits to the Air Force

Affordability

Advanced human systems integration will increase UAV affordability by reducing non-combat loss rates and reducing training costs. Adequate attention to man-machine interfaces

will act as a force multiplier by increasing productivity (more UAVs aloft with fewer personnel) and by increasing survival rates in hostile environments.

Dual Use

UAVs are unusual; they represent a major systems-level technology that has direct and obvious dual-use applications. Most dual-use successes have come from subsystem or enabling technologies, since lower-level technologies are inherently more generalizable. Non-defense government uses include: law enforcement, border patrol, search and rescue, disaster assessment and response, meteorological monitoring, and traffic monitoring, natural resource surveying, cartography, package and material delivery, etc. It is noted Washington and Oregon National Guard units have in the past used UAVs to support their local and state law enforcement activities in various operations that have extended over a year long period. User-friendly human systems integration will make UAVs more attractive to dual-use customers by improving effectiveness, reducing training requirements, cutting loss rates, and easing user reluctance to deal with a new technology. The Department of Defense will benefit from dual-use of UAV technology through reduced fly-away and maintenance costs; adequate HSI will help enable UAVs to become feasible and to be accepted in these new applications.

Joint/International Operations

Current UAV program planning documents prominently consider commonality and interoperability of systems and components. Every effort should be made to apply this paradigm to HSI. Common interfaces will help to expense investments in human systems research and will reduce cross-training requirements. Just as the hardware and software of various UAV platforms and exploitation systems should communicate in a common language, so should the human interfaces. This will become especially important if control of UAVs or their sensors is extended to the user level. In this case, the exact type of UAV or sensor should become transparent to the user. A virtual environment interface as described above, with common symbology and command language, will be a significant step in the right direction. All HSI commonality and interoperability improvements will make it easier for hardware, operators, and customers from different services and countries to work together.

Conclusions

Too often in system design an artificial dichotomy is created that attempts to classify systems as manned or unmanned. In reality there is no such thing as an unmanned system. Everything that is created by the system designer involves the human element in one context or another. The point at issue is to establish in every system, whether the system is controlled directly or remotely by humans, the *optimal* role of each human and each machine component.

For the foreseeable future the human will remain the most critical component of weapon systems. Future trends toward highly mobile deployed forces, new warfighting strategies focusing on regional threats and crisis response, more high technology weaponry including exotic weapons, and the continued importance of the environment and cost reduction, will place increasing, rather than decreasing demands on the abilities of the human component. In every potential operation humans will be required to obtain information through sensory channels, to

efficiently process the information from a perceptual and cognitive perspective, to transmit decisions or output information utilizing psychomotor skills, and to perform efficiently and effectively under a wide variety of environmental conditions.

Currently the Air Force Human Systems Technology (HST) Plan includes four major thrusts or areas of emphasis. These are:

1. Crew Systems—cockpit and display design and crew protective devices
2. Human Resources—improved selection, classification and training of Air Force personnel
3. Aerospace Medicine—biomedical factors affecting performance and awareness
4. Occupational and Environmental Health—safeguarding Air Force personnel and the civilian community from occupational and environmental hazards associated with military systems and operations

While the HST Plan provides an excellent framework for organizing and managing research and technology development, it nevertheless is highly dependent on the definition of specific mission requirements. To date primary emphasis has been placed on meeting the requirements of *manned aircraft systems.*

In anticipation of the expanded role of UAVs in the Air Force of the future it is the recommendation of this panel that the necessary resources be directed toward the initiation of research to define the optimal human/machine interfaces for the control and operation of *remotely controlled vehicles.*

Appendix L

Global Presence

Introduction

Those aspects of human systems technology necessary to exert global presence are expressed primarily in the area of monitoring and assessing a potential adversary's actions and in the attributes needed to exert presence in the context of the principles of war. In this latter case, those attributes of responsiveness, persistence, flexibility, and survivability are of special interest. In the first instance, monitoring and assessing, the development of human-centered tools for determining global (or at least regional) situation awareness is critical.[1] In the latter instance, attributes for warfighting, human-centered technologies are important in responsiveness (global reach), persistence (continuous operations), flexibility (training[2]), and survivability (coping with threats, on the ground as well as in the air). Careful attention to the tools we provide to our warfighters can markedly influence our likelihood of success in future conflicts. This appendix will address the following areas:

Fatigue/Circadian Rhythms—related to responsiveness and persistence

Logistics—related to persistence

Chemical/Biological Warfare—related to survivability

Fatigue/Circadian Rhythms

The development of a fatigue management system will attenuate the effects of sleep deprivation or circadian disruption on human performance. The military impact and application of these techniques are immense. Chronopharmacological methods for applying stimulants or sedatives (ergogenic compounds) at the right time can sustain the warrior and end a conflict quickly. Sedative antagonists (antidotes) are included to quickly animate the soldier in the event of an emergency. Non-pharmacological napping and sleep training techniques are proposed that maximize the restorative ability of sleep in the least amount of time. Finally, readiness to perform metrics will assess the quality of the rest received and the likelihood of individual success. The nation with the most substantial technology to fight at night and to sustain the fight over days and nights will have a decided advantage over one without these capabilities.

Assertion

Enhanced techniques for sustained operations will double and triple the length of time flight crews, commanders, and ground personnel can remain in action and thereby bring a conflict to the quickest possible resolution. Individuals will be able to remain alert and effective for two or three days at a time and maintain operations non-stop or with precisely timed naps. Efficient sleep techniques will enable maximally restorative sleep to return crews to active duty in the shortest possible time. Long range fighters, bombers, tankers and transport operations can

1. See discussion of Human Information Processing/Decision Making in Appendix F.
2. See discussion of Precision Guided Training in Appendix I.

be launched from stateside bases, reach anywhere on the globe within hours and return or stay and continue their mission without the debilitating effects of fatigue and circadian desynchronosis. Finally, the aggressor will be denied effective sleep, which will weaken their will and their efforts to continue hostilities.

Importance to the Air Force

The most dangerous consequence inherent in the Air Force policy of Global Reach and Global Power is incapacitating fatigue. Current missions require 20 and 30 hour duty days to cover the distances involved and have fewer crews to fly them. Mounting sleep inertia will reduce crew effectiveness and threaten mission success. Increasing reliance on night operations will force crews to perform complicated, highly technological tasks when they are least vigilant. Developing a system of physiological, psychological and ergogenic techniques that manage fatigue and circadian desynchronosis will blunt these threats.

Key Technologies

There are at least six areas of development that will be needed to optimize a fatigue management system. These will be discussed individually. All that would be necessary to implement each area in the system is a brief, focused research project to address their unique military applications. The technology exists to put the system in place in a short amount of time and then to refine the system as new techniques become available.

1. Refine the military use of ergogenic (stimulants, sedatives) agents and determine the duration of their effectiveness. The effectiveness of the stimulants in antagonizing fatigue is reflected by their widespread use in war since their discovery in the 1930's. Newer, more effective stimulants have been developed and need to be studied to determine how long they can enable combatants to remain effective and if they can be used over several days. Stimulants offer the possibility of blunting the effects of circadian desynchrony and of maintaining vigilance day and night for several days. The benzodiazepines are an effective means to induce restorative sleep. Newly developed antagonists to benzodiazepines sedation (flumazenil) may provide a means to rapidly awaken crews during an emergency. Newer sedatives, like the pineal hormone melatonin, may promote a more physiological sleep without the need for antagonists in an emergency. The maximally effective timing of these compounds needs to be assessed. Finally, the military applications of these compounds, in particular the duration of the effectiveness of stimulant/sedatives combinations needs to be assessed.

2. Develop optimal sleep hygiene/training techniques and determine the extent of their effectiveness. A research effort to determine the optimal nap duration and timing needs to be implemented to determine how long the least amount of sleep can maintain performance. Sleep hygiene information needs to be developed for operational use. New advances in sleep training (stress-reduction/muscle relaxation techniques) need to be exploited. Research should evaluate the ability of nutrition to reduce fatigue stressed performance. Meals could be developed that promote sleep (e.g., tryptophan rich) and to fortify wakefulness (e.g., tyrosine).

3. Develop rapid and reliable readiness to perform metrics and incorporate them into crucial aspects of operations (scheduling, crew feedback). Subjective assessment of fatigue's influence is often inaccurate. Crews too eager to accomplish the mission are likely to deny the experience of dangerous levels of fatigue that would threaten the mission. Cognitive tests that could be taken in a few minutes and could accurately identify impaired performance are being tested in industry. Such tests would enable managers to better assess fatigue and make the most of the human resource. Physiological monitoring devices (i.e., heart rate, eye blink or brain wave) have not progressed as quickly as the cognitive tests but offer the promise of continuous monitoring without interfering with performance. For the moment, the tests seem more suitable for monitoring type tasks, like piloting, C^4I or weapons officers' tasks. The implementation of these tests into operations needs to be studied as does the frequency with which they would be needed to accurately identify fatigued performance.

4. Develop a means to generate fatigue management recommendations given any conceivable mission. A computer program could be developed that would suggest the best available techniques given the mission demands. This would include sleep schedules, duty day length, nutrition and exercise for optimal crew utilization. Crew demands for long duration missions are different for fighters and bombers. Such a system would individualize the management recommendations for long missions.

5. Develop means to rapidly manipulate the circadian timing system. The ability to eliminate the debilitating effects of circadian desynchrony would enable crews to function more efficiently immediately upon arrival. Although ergogenic agents would provide an effective means to manage circadian disruption, new techniques to manipulate the biological clock provide an alternative. Timed light and melatonin administration are recent techniques under study in this regard. Some breakthrough may occur which would dramatically reduce the effects of rapid transmeridian travel on human performance.

6. Deny the aggressor effective sleep. Disrupted or fragmented sleep reduces the effectiveness of sleep and cumulative sleep debt accrues. It may be possible to deny the enemy effective sleep and such techniques should be explored. For example, extremely low frequency radio signals may reduce the normal nocturnal melatonin surge and disrupt sleep. People living near high frequency power lines often complain about insomnia. The use of these signals to disrupt sleep needs to be explored to determine their viability. Random attacks either by actual bombers or remotely piloted planes that would force the aggressor into the bomb shelters also would disrupt a restful sleep.

Hurdles

Existing technologies could be used to implement the fatigue management system. Many of the pieces of the system are currently under development but not strictly with military applications in mind. The primary hurdle is this lack of information on the topics discussed above

as they relate to operations. A research effort to optimize these techniques would make them powerful tools for the commander needing to expect and get the most from the troops. How these technologies can be maximized for the warfighter, and how they can be trained and implemented needs to be the focus of the research effort.

Hurdle Impact

All of the technologic hurdles are presently surmountable. Improved techniques for sleep and for rapid circadian shifts can easily be envisioned. Research commitments would send a strong signal to industry that fatigue is an area that must be considered more responsibly in design. Operationally we must acknowledge that coping with fatigue is a force enhancer and vital to achieving military goals.

Benefits

A successful fatigue management system would enable air and ground crews to function anywhere on the globe for extended periods of time. Less fatigue would mean safer operations, both at night and the days following.

Affordability

The fatigue management system envisioned has an extremely favorable cost/benefit ratio. It is important to consider how expensive the loss of a plane to fatigue related error is compared to the investiture of research support for this area. Indeed, the cost of just one of today's highly technological aircraft far exceeds the price of the research effort proposed. It is tempting to speculate how many aircraft, especially night operating aircraft, have been or will be lost due to fatigue related errors.

Commercialization and Dual Use

Government officials and business personnel would benefit greatly from techniques to reduce the effects of circadian desynchronosis as international activity is increased. Emergency police, medical and other city workers could function effectively for extended periods of time in a crisis. There already are small companies dedicated to some of these issues. They cannot address the military issues of these technologies adequately, but their efforts would be strengthened by government support and awareness of the problem with fatigue.

Providing techniques to make night operations safer and sleep more efficient would find widespread application in shift work. There is evidence of a sleep debt widespread in our society (a national sleep debt has been postulated that is regarded as potentially more serious than the national debt in terms of lost productivity and risks to health on the job). Techniques to improve the quality of sleep people obtain would find use in all aspects of society.

Joint/International Operations

Rapidly pre-shifting individuals traveling great distances for business or government purposes would increase the time available for resolving issues.

Logistics

Scientific visualization has become an important tool for most engineering domains. Computer graphics workstations generate compelling visual displays that aid scientists in understanding molecular structures, help statisticians understand complex data relationships, help architects explain their designs, and so on. With the aid of computer animation, 3-D data definition, and various rendering techniques, realistic simulations of many different products can be created to support engineering design and product prototyping.

This visualization paradigm will add a new dimension to logistics simulation and automation. Computer-aided design (CAD) tools already permit realistic 3-D imaging of product geometry and seamless integration of engineering analysis and manufacturing data. Electronic mock-ups, using animated 3-D graphics and virtual reality interfaces, will promote a concurrent engineering role for human-centered aspects of system support. It will be possible to visualize critical maintenance and repair tasks, detect and correct sources of human error, and generate maintenance instructions (tech manuals, job aids, etc.) automatically from the CAD screen. Digital design archives will allow human-centered system support elements to be revisualized and reverified when systems or subsystems are modified.

With emerging technologies, analysts and users can enter, navigate, and manipulate a CAD virtual world. It will be possible to verify critical equipment operation and maintenance tasks by allowing real persons to work with virtual tools in virtual work spaces. Task analysis supported by these technologies will have many human-centered applications. It will be possible to describe job/task ability requirements, to specify tool and support equipment needs, to identify safety problems, and so on. More important, it will be possible to make design changes to accommodate human limitations and capabilities and to visualize the result. With associated advances in natural language processing, it will be possible to generate maintenance instructions automatically. Combining these instructions with CAD graphics of human forms will make automatic generation of electronic technical manuals feasible.

Visualization technology will permit operational logistics issues to be modeled with greater realism and larger consequence than they ever have before. For example, the movement of military material through aerial ports might be simulated graphically to identify bottlenecks, optimize warehouse space and resource utilization, and manage air and ground transportation scheduling. Logistics command and control centers might have real time pictures of the status of critical cargo in transit, port and depot operation, and airlifter location across the globe. Managing these assets more effectively would have force multiplying effects. Making 3-D animated visuals available for training simulation of logistics management war skills would leverage training dollars.

Distributed interactive simulation will allow logistics assets and processes to participate directly in wargames for training and readiness assessment and in virtual prototyping for new/altered systems. For example, new concepts for aerospace ground equipment can be tested on the same electronic air/land battlefield used to evaluate new fighter weapons or tactics. Visualization is a critical feature of the virtual prototyping approach advocated for concept evaluation and defense acquisition decision support.

Assertion

Information on system design, support, and modification will be available in digital formats. In many cases, this information will be carried in the prime systems themselves. In other cases, it will be possible to reverse engineer system components to permit digital "remastering" of manufacturing and logistics support data. Digitalization of product data, combined with low cost computing power, will permit human-centered aspects of system operation and maintenance to be simulated and fully verified before hardware is produced. The cost of producing logistics support items, including technical manuals and training media, will shrink by an order of magnitude.

Visualization technology will allow this simulation capability to extend to all other logistics processes. At present, computer graphics permits simulation of human figures for electronic maintenance task analysis. The same technology, augmented with virtual reality devices, will permit real-time imaging for simulation of material movement, remanufacturing and industrial repair planning, and logistics command and control, among others.

Importance to the Air Force

Historically, the majority of system ownership costs have been in logistics support, and the majority of logistics support costs are human-centered ones. Bringing down the cost of maintenance manpower, technical data, and training requires focused application of visualization technology during system design.

At the same time, the cost of logistics-oriented design evaluation analysis must decrease, and its scope must increase. Visualization technology, which couples low cost computer graphics simulation, virtual reality devices, and high speed digital network technology, is the surest route toward these objectives.

Air power in the future will rely increasingly on air mobility. With fewer forward operating bases and a wider array of potential missions, the Air Force needs both longer legs and a shorter tail. Reducing the deployment footprint means limiting the need for people, equipment, and parts at forward locations.

Force modernization cannot rely on new airframes but on a mix of new systems and system upgrades/modifications. Both acquisition strategies will place a premium on reducing logistics support requirements. Accordingly, research investments aimed at affordability are to be stressed. Logistics visualization is a key enabling technology for this.

Key Technologies

Computer Processing Speed

A computational approach to logistics visualization anticipates continued expansion in data processing speed through hardware and software design innovations. In addition, the cost of computer processing must continue to decline. This is a general technology need, but it is particularly important for visualization, which is extremely computationally intensive. Transmission rates and network bandwidths must increase dramatically, or else new data compression algorithms must be devised, before substantial progress can be seen.

Visual Displays

Current helmet-mounted displays have low resolution. Numerous efforts are under way to make them less cumbersome, less disorienting, and more visually realistic.

Haptic Displays

Often, it isn't enough to see a virtual environment. For many applications, it is necessary also to be able to manipulate virtual objects. Technology for tactile and force feedback is being worked on at many places. The best available technology is not nearly good enough. In many ways, the technology challenges for haptic displays are more daunting than those for visual displays.

Hurdles

The key hurdles to be overcome will include:

1. Defining and standardizing criteria for human problem solving and decision making, particularly in the context of wing level logistics command/control
2. Applying this knowledge in an integrative fashion to the development of display concepts
3. Development of software/hardware to function in this human-centered approach to logistics command/control

Of the three hurdles, the first is critical to set the parameters for the other two and is likely the most difficult. Resolution of the multi-variate issues in problem solving/decision making will require not only focused teams in this particular area of logistics command/control, but also will depend upon a loose federation of teams from battle management, information technology, and basic academic research. Funding for additional basic research *may* be required. Out year funding for advanced technology development will be essential.

Benefits

Affordability

Techniques that reduce system development time will also reduce system development and ownership costs. Visualization, making use of CAD and Virtual Reality technologies, will allow design evaluation of many different logistic support options. It will allow implications of different support options to be communicated clearly since it relies on "seeing" problems and solutions.

Commercialization and Dual Use

Visualization technology is an important element of national investment strategy that has synergistic benefits for the private economy. Leadership in the key information technologies is essential for continued economic growth and national security. Advances in visualization technology will further US leadership in such critical industries as bio-medicine, pharmaceuticals, communications, flexible manufacturing, and aerospace. Examples of products/services that will benefit from visualization are telesurgery, molecular engineering, high definition

television, robotic factories, and space-grown crystals. The transportation and shipping industries will especially benefit from newtechnology allowing visual simulation of distribution channels across the globe and across the warehouse floor.

Deployability

Attention to Reliability and Maintainability has been credited with the high availability rates seen in the Gulf War. Yet the airlift requirement remains very high for effective employment of air power. Deployability, that is, pallets moved per unit, is becoming a key metric for the Air Force. Visualization technologies will allow designers to verify the reliability of components prior to manufacture and use. Likewise, these same techniques will permit maintenance actions to be modeled and simulated to determine the best procedures for repair actions. Together, the systems developed using visualization technologies will provide greater measures of deployability.

Logistics Planning

Reducing the weight/volume of logistics support needed for deployment is an emerging requirement. Lean Logistics and Two Level Maintenance are current examples. Historically, logistics support has been based on a "push" concept that moves thousands of items forward regardless of specified demand. This assures a high degree of readiness but at very high cost. Logistics simulation tools based on visualization will help in transitioning to a "pull" concept that allows specific items to be dispatched and tracked separately. In short, logistics support becomes more efficient because it can be tailored to specific needs.

Chemical/ Biological Warfare

This section considers opportunities for technological advances bearing on Air Force concerns for the threat of chemical/biological (C/B) warfare. This section recognizes the fact that the Congress has assigned to the Army the mission to achieve technological advances on this subject. Nonetheless, the Air Force has significant responsibility to be able to operate in the C/B warfare environments and must continually address this subject for several very important reasons:

- The threat to airbase operations must be understood and quantified
- Changes to the threat must be recognized immediately
- Operational responses to the threat must be evaluated, and capabilities to respond must be improved
- Aspects of this subject unique to the Air Force must be identified
- Technological advances, from whatever source, must be evaluated for Air Force applicability

The threat of the use of C/B agents by an adversary in future conflicts should not be minimized. C/B agents are relatively inexpensive, fairly easily used weapons, primarily for anti-personnel purposes. They can either incapacitate an exposed population and overwhelm the medical channel or they can kill (rapidly as well as slowly). The mere threat of exposure is likely to result in the use of protective equipment which today seriously degrades mission

performance. The Air Force, in contrast to the other services, operates from fixed bases that are readily pinpointed and are high-value targets. The area of an air base is relatively small, making it susceptible to a C/B attack from a very small number of C/B weapons. Due to the environment in which the Air Force carries out its mission, non-lethal doses may make mission completion impossible and even a small number of casualties will significantly hamper generation of sorties. Movement to non-contaminated airfields, while perhaps possible, cannot be done without reducing the intensity of the air war and providing a respite for the enemy.

The simplicity of delivery, the real and perceived threat of the use of C/B weapons, and our difficulty in having an appropriate response to their use, makes it imperative that the Air Force understand fully how to cope with this threat.

Assertion

By the year 2020, all aspect of chemical and biological warfare involving Air Force operations will be simulated, and this simulation will be integrated into all other Air Force and Joint Service simulations. The critical aspects of warfighting in the C/B environment will be solved. Agent detection, both on-site and standoff will be available. In the event of an attack, equipment and critical terrain can be rapidly decontaminated. Personnel protective ensembles, compatible with mission accomplishment, incorporating personal dosimeters and exposure safety monitors will be widely used. Our ability to model this environment, coupled with our known ability to fight successfully under these conditions, will be a major deterrent to the use of C/B weapons since a potential adversary will be able to see that he has little to gain by their use.

Importance to the Air Force

This assertion is important to the Air Force since we must be able to test and evaluate its operational capabilities against this threat, as it must against all threats. Because of the complex nature of airbase operations in a C/B environment, test and evaluations using real Air Force units are enormously expensive, and, due to the constraints of safety and policy, are not extremely useful. Modeling and simulation will offer an affordable alternative, better than the current situation. Since the threat will likely increase over time, the development of sophisticated models will provide the gold standards to assess defensive responses to C/B agent attacks. Additionally, the ability to detect agents, coupled with the ability to decontaminate in the event of an attack, will make it possible to wage war without any degradation. The development of new personnel protective ensembles will make it possible for those individuals required to work in the C/B environment to do so without degradation of functional capability.

Key Technologies

In the simulation technology area, the capability has been progressing at a rate sufficient to achieve the robust capability needed by the year 2020. We have a rather comprehensive data base dealing with the consequences of C/B warfare. The task to achieve total simulation is admirably suited to incremental progress, delivering direct operational benefit with each step forward.

In the area of detection, decontamination and protective equipment, the technology base needs to be improved. Advances are within the realm of reason, but the science must be reduced to practice.

On-Site Detection

Specific agent identification is achievable now scientifically. Biomedical science has identification procedures of all microbes and toxins affecting humans and can quickly devise identification methods for new agents. However, the time currently required to identify an agent is too slow—it must be in minutes, not hours or days. Environmental samples for identification are often contaminated with irrelevant chemicals and microbes, as well as with non-specific particulates like dust and sand. Filtration is required to concentrate/purify samples of interest before they are usable for testing. Progress in the science of filtration will likely determine success or failure in C/B detection.

In addition, the science of producing a signal unique to each agent, then isolating and amplifying that signal into an alarm, is within reach now. The final hurdle is in engineering, to integrate into one device the capability to identify all C/B agents. According to some, such a device is an unachievable goal, and most certainly is very expensive to produce. Logically, individual agent alarms would appear to be more achievable, affordable, and suited to delivering improved detection capability incrementally.

Stand-off Detection

Stand-off detection is not achievable with today's science, unless a sample can be collected and interrogated at some distance (kilometers) from an airbase. An UAV, suitably equipped, could do the job. The alternative of interrogating a distant location by directed energy, stimulating the formation of a spectrum of identity, and reading that spectrum, has been a topic of research for 20 years without success. The UAV option takes on more feasibility, as micro- and even nanoscale manufacturing becomes a reality and is applied to C/B agent diagnostic devices.

Protective Clothing

The science of textile composition, structure, and manufacturing will result in new textiles that "breathe" in one direction only - outward - to dissipate body heat. This same science will produce fibers with characteristics that allow reactive compounds to be attached to them (extending the presence model of water repellency). The status of progress in these advances in industry is proprietary, but the economic incentive for achievement is certainly there for civilian applications. Such textiles could assist in resolving the body-heat buildup problem in the present C/B protective ensemble, and assist in C/B decontamination of personnel by having agent-detoxifying compounds attached to them. Application of these new textiles to Department of Defense needs would depend upon their performance in wet climates and on the 100% surety of their "one-way" characteristic.

Protective Mask

In the Air Force experience, protective mask fit is a big issue. Active personnel, over time, move so as to compromise the secure fit of the mask, and become casualties. The alternative is not to worry about fit by creating a positive pressure inside the mask. (Soviet tanks have been designed for C/B protection with positive overpressure of internal vs. external air for many years and even their hospital ships have this features.) Positive overpressure is standard in high hazard microbiological laboratories where 100% surety is demanded and delivered. Positive

overpressure inside a protective ensemble, achievable now technically, will be even more feasible by virtue of micro-manufacturing of blowers and availability of micro-power sources. Widespread Air Force use requires these manufacturing and power source advances.

The mask could then be integrated into a hood, like present day suits for hazardous material spill clean-up crews. Such hoods have wider plastic windows for greater field of view. The addition of microphones and receivers, based on hearing-aid technology, will solve the present communication problem. Micro power sources can drive a small portable cooling system to control heat build-up. These advances are commercially driven by environmental clean-up requirements. It must always be remembered that even with the best individual protection, airbase operations cannot proceed effectively without collective shelter protection for rest and recuperation.

Decontamination of Equipment

Improved decontaminants are being devised in the laboratory for chemical agents and for toxins from nature. The science of sterilization provides specification for destroying microbes. As elsewhere, this knowledge base requires practical delivery systems to be of value to the Air Force. Currently decontaminants can be highly toxic to humans and highly damaging to components and materials in aircraft. Future generations of decontaminants must be much better targeted. The most complete way to decontaminate anything is to do it in a closed space, with the decontaminant in aerosol form. This technology exists in the agricultural industry, where fogging of produce, under pressure, to reduce spoilage is routine. Aerosolized delivery of active decontaminants under pressure is exactly what is required to reach small and inaccessible locations of aircraft, for example.

The Air Force could also take advantage of strategies devised by the sporting industry for year-round sports, like tennis: positive-pressure bubbles large enough for two or even three tennis courts. Such bubbles could be made to order for decontaminating aircraft, with a smaller version suitable for decontaminating parts and components before shipment for repair, currently a "too-hard-to-do" function.

Decontamination of even localized pieces of terrain probably will not be achievable, except by waiting for the natural decay cycle of agent (sunlight is a natural decontaminant) to be completed; some microbial agents resist natural decay for years.

Hurdles

The technology advances likely can be achieved. Key difficulties will be encountered in the area of remote or stand-off detection. Aspects of agent detection and identification at distances sufficient to take defensive action pose difficult problems. In the modeling/simulation area, validation/verification of the model and the simulation will be key factors in determining the overall suitability and impact of this approach. Finding new ways to assess capability and intent of an adversary are also difficult issues that bear watching to make sure progress is being made.

The Air Force needs a firm commitment to this area, with adequate funding to make sure that the long-term support is there to build and maintain this capability to produce solutions to

this critical problem. Coupled with this support, we need to find ways to understand offensive attics that might be used against us to insure that we indeed are preparing for the proper type of threat.

Counterproliferation

Counterproliferation is a national security priority of the present administration. Multiple federal agencies have responded to this priority requirement. The principal Department of Defense contribution is technology, and also intelligence. A principal Air Force concern is destruction of chemical and biological warfare weapon and agent stockpiles and the capability to produce them.

"Counterproliferation" means prevention of weapons of mass destruction to countries without that capability now. It also means containment/neutralization of proliferation in countries suspected of having already acquired a capability or building one. Counter-proliferation also focuses on terrorist groups.

"Weapons of mass destruction" include, in the view of many, chemical and biological weapons as well as nuclear weapons. That is an oversimplification. Nuclear weapons fit this designation. Chemical and biological weapons fit this designation only if their use disrupts the infrastructure of a society so that societal organization breads down or stresses the infrastructure to a maximum without actual breakdown. But chemical and biological weapons can be used against point targets and against single individuals. Used in these modes, they are referred to as "unconventional weapons" to distinguish them from conventional explosive ordnance. By this logic, weapons of the future, non-explosive in nature, would be included in this designation.

Monitoring of nuclear weapons and their proliferation has been on-going since the nuclear age began. Efforts on chemical weapons have also been on-going for a long time, with similarities of approach to those used in nuclear monitoring. Counterproliferation efforts today follow similar pathways.

Biological weapon monitoring and counter proliferation efforts are altogether different. The technology base for biological weapons includes the sciences of microbiology, molecular biology, and genetic engineering. These sciences are already global. Microbiological reference services, including those supported by the US government, distribute to anyone claiming a legitimate scientific need whatever microorganism is requested. The microorganism will arrive with a detailed pedigree and instructions on how to maintain it. the inevitable conclusion is that the potential for biological warfare has already proliferated globally.

Making biological warfare agents is easy to do, and cheap. Even the delivery systems can be simple, especially for use by terrorists and special forces. Battle field delivery of biological weapons is more complex but not very difficult, merely substituting one payload for another. So the global threat is very real.

There are three general responses to this threat available to us: technology-based defense, expansion and enforcement of the biological warfare non-proliferation treaty, and mobilization of world public opinion against the use of biological weapons. This last response is the preferred one, because the other two responses are hard to accomplish. However, we must pursue all these responses simultaneously if we are to contain the problem.

Technological defense is principally detection. General awareness that perpetrators can and will be caught is itself a strong deterrent. (Although it may not be a deterrent for ideologues.) Biomedical science has already produced specific identification procedures for all known and potential agents affecting humans and animals, based on very specific immunologic reaction, physical characteristics, high-resolution microscopy, spectral analysis, and DNA matching. (Identification of agents vs. plants is a different matter.) During peacetime, for counterproliferation purposes, all of these technologies can be brought to bear in a controlled laboratory setting on field-collected specimens. Specific identification by remote sensing is probably not achievable.

The manufacture of biological warfare agents does not have any specific or general signature. Inferential analysis is useful, however. Human intelligence is of paramount importance.

The central issue for the Air Force in all this is delivery of ordnance to destroy chemical and biological weapons stockpiles and manufacturing facilities. Avoidance of agent dispersal in the process is a necessary condition. Progress on destruction starts with specifications of sterilization of infectious agents and detoxification of chemicals, and then extends to strategies for control of these reactions. The science base is in place for eventual success.

Benefits

Commercialization/Dual Use

A challenge for ingenuity is to find in the civilian sector a technological requirement that matches to a degree the military's need, then piggy-back on it or join forces with it. Consider BW agent detection. Speed of identification is the very most important specification. Where in the civilian sector is there a similar requirement? In commercial meat inspection.

Coliforms, salmonellae , and other organisms can contaminate meat and poultry. These contaminated foods, consumed undercooked, can cause death form food poisoning. Improved monitoring for microbial contamination is a high-priority US Department of Agriculture requirement. But, meat and poultry production lines are very high speed out of commercial necessity. So improved monitoring will have to be fast and accurate, not an exact parallel to C/B agent detection needs but close enough for relevance.

Other parallel military/civilian requirements certainly must exist. They have to be looked for as part of a new way of pursuing national security technology goals.

Conclusion

All three areas identified in this appendix are critical to the Air Force maintaining Global Presence. Management of fatigue provides the tools to allow aircrews and support personnel to sustain operations over a longer period of time. Visualization of the logistics process will permit the end to end inclusion of logistics considerations in the design process, as well as vastly improve the logistics planning process for wartime and contingency operations. Advances in C/B detection and protection will allow US troops to maintain the wartime tempo under adverse conditions without degradation of performance. Research in the technologies identified in this appendix will enhance the Air Force's ability to achieve this vision.

Appendix M

Biological Sciences and Biotechnology

The biological sciences are the most fertile field in science today. It is likely they will continue to be for the foreseeable future. How can this fertile ground help the Air Force? During Desert Shield, some very innovative S&T was done rapidly on bio-warfare agent detection by Air Force scientists at the Armstrong Laboratory and detection units based on this S&T were fielded. Looking to the future, what are some of the Air Force-specific needs related to the current revolution in the biological sciences and biotechnology? The Air Force needs fall into two categories: those directly related to human performance, and those involving improvements to Air Force weapon systems themselves.

Human performance requirements across the array of Air Force missions are truly extraordinary. They constitute human performance at the very limit of the human body to survive, literally. Maximum g-forces, 36 hour continuous flight missions, abrupt shifts from day to night through many time zones, superimposed on other stressors, are some examples.

Increased knowledge of human body processes will allow design of very specific procedural and pharmacological interventions to enhance human performance and to restore or retard degraded performance. The central issue here is compatibility of these interventions with Air Force mission requirements, especially requirements for abrupt unexpected changes to these missions. For example, better sleep inducers will become available from the civilian market but can that sleep be interrupted with no loss of "awake" performance? For civilians it does not matter because they rarely have sleep interrupted for business reasons. That is not so in the military. All present drugs have side effects which are undesirable. However, it possible to forecast that some drugs, especially those acting on the brain, will be so specific in their action, that there are not "other" actions (i.e., side effects).

Improvements in the performance of Air Force weapons systems through biology can be forecast but with much less specificity than for human performance. An overarching concept receiving ever broader recognition in science today is that the hard sciences can learn from a close examination of biological structures and processes and can adapt these for use in the synthetic world. There already is a spectacular example of this concept in computer science: neural networks. Other examples are on the horizon, or closer.

This appendix presents examples of future enhanced Air Force capabilities, and the technologies involved, having to do with both human and weapon system performance. No attempt is made to be comprehensive. The examples will probably suggest to the reader other applications of biology and biotechnology to enhance Air Force capabilities.

Example One: Drug Enhancements of Memory

Assertion

A drug of exquisite specificity will be available to enhance memory and its usefulness in enhancing situation awareness will be demonstrated.

Essential Orienting Background

- Memory is not just the device we use to remember things but is the basic device we use to organize the entire world around us
- Many parts of the brain are involved
- The brain's memory storage capacity is unlimited; it cannot be saturated.
- The brain stores memories by breaking them into their parts even though the memory is recovered in a seamless total fashion
- A single memory consists of a network of neurons (nerve cells), each of which has been stimulated so as to have a long-term increase in membrane potential; this means that this network's behavior has been altered; later, the brain can search, find and "fire" this network, recovering the memory in a second or less
- There is a hierarchy in the way the brain stores information
- The brain unconsciously organizes memories by categories, using different parts of the brain for each: the first level is by time sequence of events; the next level is by physical similarities; the next level adds emotional and muscular power (movements) components; in a fourth level, there is the memory that 1) records the passage of time, 2) records routine matters which are erased after a brief period, and 3) records expectations and anticipations (i.e., whether something that is occurring is right or not right)
- Beyond this, there is another 85% of the cortex of the brain still to be unraveled as to function, connected only to itself, and talking to itself all the time; when we know why, we may have a comprehensive theory of brain function
- A hypothesis is that the frontal area (where physical movements of all kinds are organized) is communicating with the back of the cortex where vision and other sensory perceptions are accomplished
- This front-to-back link may be the essential element of uniquely human brain activity (i.e., imagination, thinking, planning)[1]

Scientific Feasibility[2]

- A neurobiological interpretation of situation awareness includes the idea that situation awareness is forebrain specific, involving attentional breadth without sacrificing focus of attentional detail

1. Discussion derived from a Los Angeles Times (1993, Nov 14) interview with Dr. Gary Lynch, U.C. Irvine.
2. Discussion with Professor Granger, U.C. Irvine. June, 1995.

- By far the most numerous neuronal synaptic receptors involved are glutamate receptors of a specific type (AMPA)
- Different sub-types of the AMPA-type glutamate receptors reside in different cell types (excitatory/inhibitory/modulatory, feed forward/feedback, different layers) and in different brain regions, subserving different cognitive functions; selective targeting of specific subtypes of AMPA-like receptors may enable differential enhancement of particular mental faculties
- A new class of drugs, called AMPAkines, has been designed which enhances transmission at these receptors in animals and improves both rate and retention of learning
- Also this class of drugs increases activity in attention-based tasks without non-specific arousal such as would arise with stimulants like caffeine or amphetamines
- Members of this class of drugs are now in testing in humans for safety and efficacy

Applications

- Primary medical application is to attempt to restore memory to patients with Alzheimer's disease
- Possible other uses include enhancement of learning and memory in healthy individuals

Importance to the Air Force

- A recent analysis of Situation Awareness (SA) by the Armstrong Laboratory identified excellent working memory as one of the skills associated with high proficiency in SA
- Therefore, enhancement of working memory by AMPAkines may be useful in improving overall SA
- However, many aspects of this possible use must be examined for safety and true efficacy, as well as indications for use in order to optimize the presumed benefits

Example Two: Workload EEG Monitor

Assertion

A multiple-task workload/cognitive effort monitor - an enhanced electroencephalograph (EEG) - will be available to adjust operational displays and training devices to the changing state of brain performance of the operator/user.

Scientific Feasibility

- An EEG collects signals from the scalp which are representative of neuronal activity immediately underneath on the brain surface

- An EEG has been constructed with 128 sensors instead of the 19-20 sensors found in medical diagnostic machines; a 256-sensor machine is in development
- Signal selection and processing has been greatly improved and software for signal interpretation has been greatly refined; further progress is a certainty
- With this enhanced EEG, mapping of brain activity during various mental functions is advancing rapidly; some EEG maps have already been validated directly on exposed human brain during neurosurgery!
- The EEG sensor array is embedded in a skull cap worn with complete comfort, shielded from exogenous electro-magnetic radiation
- Multiple-task workload/cognitive monitors can be performance-based, subjective or physiological; to be integrated into any system and be totally unobtrusive, operator monitoring can only be physiological; the enhanced EEG fits the Air Force requirement
- Physiological indices of workload/cognitive effort can be acquired from cardiac monitoring and monitoring of various eye function parameters; monitoring brain function will allow more accurate parsing of human workload responses; brain monitoring is the frontier
- The enhanced EEG is now being used in various scenarios in simulators

Applications

- In skill training, to pace instruction and adjust the scope and complexity of instructional material to the individual trainee's capability to learn
- In operational environments, to identify when operators are fatigued, and the degree of fatigue, as by napping during flight or on the job on the ground
- In operational environments, to adjust information formatting, content of displays to optimize the effort required to perform the mission in high and low workload period (e.g., for pilots and controllers)

Challenges

- Scale up of the EEG sensor array and determination of optimum size and pattern of the array
- Interpretation of the EEG with other physiological monitoring indices
- Establish the gains from use in training
- Establish the gains from use operationally

Importance to the Air Force

- Adaptive workload/cognitive effort monitors will revolutionize individual skill training; training costs will go down, training effectiveness will go up, many training dollars will be saved

- Use of the monitor in operational environments will have big payoffs in proficiency of mission execution and in safety

Example Three: Brain Activated Control of Machines

Assertion

A brain activated control (BAC) system will be perfected for use by pilots to control selected functions when physical movement is constrained (e.g., during high acceleration) and when workload is high.

Scientific Feasibility

- BAC systems based on the EEG have been validated in laboratory settings
- EEG sensors are used to detect brain signals, with the sensors applied to the scalp at precise locations overlying the site of brain action (e.g., back of head visual cortex)
- Two different sources of brain-activation can be used: endogenous (i.e., thinking), and exogenous (e.g., response to modulated light stimulus); conceptually, endogenous stimulus is preferred but is very hard at the present time to isolate the signal from all other brain activity
- With exogenous stimuli, timing is facilitated and the operator can be trained to vary the amplitude of the steady-state visual evoked response, measured at a specific frequency (e.g., 13.25 Hz); amplitude above or below a preset threshold, maintained for a specified length of time, is captured as a signal (+ or -)
- This signal becomes the device control
- A hybrid system combining EEG signals with forehead muscular activity (using an electromyograph) has also been devised
- Yet another EEG system focuses on the motor cortex, and employs neural networks trained to recognize EEG patterns which precede specific body movements by a fraction of a second; this approach represents the beginning of a control device based on endogenous brain stimulus

Applications

- BAC has obvious benefits for severely handicapped individuals who are fully competent mentally
- BAC also can be used by paralyzed patients to stimulate muscles electrically to prevent atrophy; the ability to control this external device is an enormous morale booster for these patients
- BAC also can be applied to video games and is being pursued vigorously by industry
- BAC has the potential to accomplish selected control functions in any constrained or high workload environment

Challenges

- To reduce the potential for errors by BAC
- To achieve real-time BAC
- To develop more effective control logic, balancing control stability with system responsiveness
- To develop an EEG dry electrode recording system
- To integrate BAC with already mature Helmet Mounted Display technologies

Importance to the Air Force

BAC is an alternative control option that must be considered for inclusion in high acceleration, high workload aircraft cockpits.

Example Four: Human Body Structure/Function Modeling

Assertion

Human body structure/function will be largely understood, modeled, and integrated into machine design.

Scientific Feasibility

- Current human models are primarily kinematic; they simulate motion without considering mass and force; they answer questions of fit
- Even these models represent averages; the extremes of size are not well represented, and the differences of gender are not yet addressed
- Upgrade of kinematic models depends only on acquisition of data to fill the gaps
- The general science of mathematical modeling will support extension of present human models

Applications

- Essential for accurate design of Air Force systems; the human role in the system is more accurately reflected in the initial design, thereby eliminating costly design revisions later

Challenges

Extending present models is an exceedingly complex task of comprehensive representation of human body dynamics. This includes:

- Mass characteristics of individual tissues, their aggregation into composite structures (e.g., limbs), the aggregation of structures into total body form, and then the mass characteristics of anything that the body might be wearing, carrying, or attached to (e.g., seat, helmet)

- Force and tolerance characteristics of body parts (e.g., muscle strength), of the total body, and of the structures in direct contact with the body
- Force vectors (straight line, torque, and shear) and the range and limitation to motion; also to be considered is the elasticity of body tissues, which have remarkable energy absorption and dissipation capabilities
- Characteristics of the environment surrounding the body, which may be highly volatile (e.g., ejection)

Importance to the Air Force

- Completion of this human modeling will ensure maximum life support in crash and ejection environments and ensure optimum human operator interface with Air Force systems

Example Five: Molecular Optical Information Storage

Assertion

Molecular optical information storage devices will be perfected.

Scientific Feasibility

Already the following is happening in industry:

- Materials scientists are searching for self-assembling, programmable materials for next generation of computers; DNA has both properties
- Therefore, the strategy is to copy nature: synthetic DNA has been made which is self-assembling
- Then using biotechnology, synthetic DNA has had attached to it chemical structures, some which can be stimulated to emit light (chromophores), and others which can transfer electrons; these two properties can be adapted to programming
- Next, synthetic DNA-polymers have been attached to solids, like silicon, and the special programming properties retained; thus is born a solid-state device of synthetic DNA-polymer on silicon which can be used as an information storage device, to be read optically!
- This is nano-electronics, actually nano-optronics, the gateway to the future in information technology devices

Applications

- Replace photolithography as the manufacturing approach for information storage devices
- Greatly reduce size/increase capacity of storage devices
- Replace electronic computer with a molecular/optical computer (eventually)

Challenges

- Fabrication at an acceptable cost
- Connect individual devices so as to have "soft connectivity," flexible functioning to avoid being stopped by molecular defects, which themselves may be too difficult to detect and eliminate during fabrication

Importance to the Air Force

This new world of information technology will transform present day capabilities; increasingly complex global battle management requires much faster and larger capacity devices, which this new technology will deliver.

Example Six: Molecular Optical Computer

Assertion

Molecular optical computers will be a reality

Scientific Feasibility

- Molecular computing has recently been reported for a single computational task (the directed Hamiltonian path problem)[3]
- The computer science community has suddenly taken seriously the prospect of a molecular computer[4, 5]
- These reports focus on short strands of DNA as the molecule; single strands of DNA are simply sequences of nucleotides with one of four possible components at the site which pairs with the complementary strand; that means that in a short strand of 20 nucleotides you have 4^{20} computational alternatives, a huge number
- As shown in the molecular storage device section, a solid state DNA/silicon device suitable for optical reading is being constructed now

Applications

- Massive parallel processing
- Massive search function
- Eventually, a universal computer

Advantages

- Very energy efficient compared to power requirements for prolonged use of a super computer

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3. Adelman, L. M. (1994, Nov 11). Molecular Computation of Solutions to Combinatorial Problems. Science, 266, 1021.
4. A Boom in Plans for DNA Computing. (1995, Apr 28). Science, 268, 498.
5. Lipton R. J. (1995, Apr 28). DNA Solution of Hard Computational Problems. Science, 268, 542.

- Number of operations per second will be orders of magnitude faster than present fastest supercomputers (10^{12} operations per second)

- Greatly increased storage capacity - 1 bit per cubic nanometer vs. existing media (e.g., videotape: 1 bit per 10^{12} cubic nanometers)

Present Advantages of Electronic Computers

- Performs a variety of operations

- Highly flexible in operation

- Fast on most tasks, except enormous searches

Concerns

- Errors; industry is working hard on this concern - candidate solutions are proprietary

- Is it possible to scale up, speed up, and make "dry" the present "wet" chemistry to process DNA after a "computer" run to arrive at the answer? Industry is close to solving this concern: fast optical reading of DNA instead of "wet" chemistry.

Challenges

- Find applications for a computer that does 10^{18} to 10^{20} operations per second

Importance to the Air Force

- Molecular optical computers are the future; the Air Force has information management requirements right now for this new generation of computers

Example Seven: New Materials For New Structures

Assertion

A new generation of materials, probably composites, will be available, designed after principles of hierarchical structures in nature (biomimicking), manufactured at least in part by incorporation of biological self-assembly principles and processes (bioduplication), resulting in materials having the behavioral properties of biological structures: durability, flexibility, responsive to external change, reactive to internal injury (self-repair) and/or damage tolerant.

Scientific Feasibility[6]

- Such a new generation of materials is only a dream today but the pathway to that dream has definitely emerged from recent research

- The key, already demonstrated in computer sciences with neural networks and synthetic DNA optical storage devices, is to learn from nature and then synthesize comparable structures

6. This section follows very closely material prepared by Professor Mehmet Sarikaya, University of Washington; permission for use is gratefully acknowledged.

- Biological structures, both hard and soft, are composed of just a few different atoms (Carbon, Hydrogen, Nitrogen, Oxygen, Calcium, and sometimes Sulfur and Phosphorus), yet they have a wide range of structural characteristics reflective of how they are put together (plates, fibers, cylinders; spirals, lattices, laminates; inorganics in soft matrices, usually proteins or lipopolysaccharides)
- Complete biological structures are hierarchical, with as many as eight levels, from atoms to molecules, to macromolecules, to functioning entities like enzymes, to complex proteins, to intracellular organelles, to complete cells, and finally to conglomerates of cells (tissues)
- Nacre of mollusk shell (mother-of-pearl) is such a biological hierarchy, a composite of inorganics and organics
- Some natural structures - like nacre - are far stronger than any man-made material
- The strongest man-made material is microalloyed low-carbon martensitic steel; it is probably the only truly hierarchical structure among synthetically made materials, with ten levels; this steel is used in aircraft landing gear, and armored vehicles
- Studies of biomineralization in mollusk shells are revealing nature's way to crystallize and laminate Calcium Carbonate ($CaCo_3$) into a structure that we cannot *synthesize*; this structure has mechanical properties 30-50 times higher than synthetic $CaCo_3$ and even two to three times higher than high-tech ceramics
- The key here is how nucleation of crystals starts on the soft protein matrix - the structure of the protein directs the crystalline structure
- The future for biotechnology is to scale up production of such controlling protein matrices which will then direct mineralization into forms we cannot now synthesize!
- Another example of a biomimetic opportunity with huge potential impact is bacterial production of magnetic crystals (Fe_3O_4)

Challenges

- To extend the science base evolving from a fusion of mainstream biological science with materials science
- To understand fully the genetic and other controlling factors of biomineralization in natural systems (e.g., mollusks)
- To demonstrate that bioduplication can be fused with synthetic production processes to achieve currently unattainable crystalline structures
- To demonstrate that the mechanical properties of synthetic materials can be extended beyond present maxima by employing structural concepts from nature
- To reduce to practice these and related scientific advances

Importance to the Air Force

- Eventually the Air Force must replace its current fleet of manned aircraft
- Replacement air platforms, to be credible for investment, must overcome two quite different constraints:
  - They must be cheap to make and support
  - They must be structurally/aerodynamically entirely new if they are to survive in the increasingly lethal battlefield environment
- Biomimetics is not a new science; what is new is the momentum building from solid research advances in biomimicking and bioduplication in the last five years. The conceptual framework of biomimetics probably offers the best hope of achieving the revolutionary structures which replacement air platforms must have for the Air Force to operate successfully.

Other Considerations

This presentation does not reflect all the biological topics actually considered during this New World Vistas study. One item was on the original agenda which did not come to closure: biological contributions to a new generation of sensors for structural integrity. This topic is of enormous importance, and cost, to the Air Force. Advances would yield enormous savings. A second incomplete item concerns compatibility of biological materials with flight environments.

Biosensors

There are many biosensors, some extraordinarily effective but not totally understood. Biosensors could have many applications to Air Force operations, such as to non-destructive evaluation of aircraft. The best example of a biosensor is the nose of a dog, which is trainable for detection of very specific targets, even those which do not have an odor signature that is known to science, like trip-wires (maybe they detect human scent of those who set the wires). Conceivably one might dope structural materials with biological materials which facilitate either endogenous or exogenous monitoring and interrogating functions. A standard medical imaging strategy is relevant here. Radio-opaque markers are introduced into the body, targeted by one means or another for concentration at one or more specific sites. The diagnostic imaging system portrays the distribution of these markers and the distribution is interpreted for diagnostic meaning. Suppose structural materials were "doped" with a material which an imaging system can "see." The integrity of that material would be established if distribution of the doping material is unchanged from previous imaging. One might dope with a substance that is reactive to electromagnetic radiation. Again, a distribution pattern might be observed. Its constancy means structural integrity, a change means closer examination is necessary by more traditional means to look for structural defect. No system of this sort has evolved yet although a form of hand held *Squid* is being examined for application to aircraft wings.

Unusual Microbes

Air Force systems generally have very high temperature regimes which destroy the integrity of biological materials. Biologically active materials operate in a wet environment and in an

environment which is carefully maintained in a very narrow range of temperature, pressure and pH.

The margins of the world's biological system are still being extended beyond what is known, much to everyone's surprise. New environmental domains for microbes are being discovered, with unknown potential applications. There are two examples where the conditions of survival and replication are extraordinary: organisms which thrive at vents in the deep sea floor where pressure and temperature far exceed earth's surface conditions (except for microbes in thermal fields like Yellowstone), and organisms recently found in rock cores obtained at 10,000 foot depths below the earth's surface. Both are remarkable discoveries. Both may lead us to an understanding of how to synthesize aircraft structures not now possible.